# THE HEATING OF STEEL

By

M. H. MAWHINNEY

*Consulting Engineer, Salem, Ohio*

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To

GRACE BOWMAN MAWHINNEY

AND

FLORENCE, PEGGY, AND ANNE

# Preface

The heating of steel implies a purpose for such heating, a method of accomplishing the heating, and tools for doing the heating in a manner satisfactory for the purpose.

The purposes of heating steel are a considerable part of the science of metallurgy and, since this is not a metallurgical treatise, the treatment of these purposes is largely a cataloging of the various reasons, in order to discuss the methods and tools available.

These methods and tools involve furnaces of one form or another in most cases, and a wide variety of types are available to the metallurgists and manufacturers of steel. An equally wide variety of results are obtained from their use, and an understanding of the principles which underlie their design and operation is essential to a satisfactory operation.

The purpose, then, of this book is to present a practical discussion of those features of heating methods and of furnace tools which are important in obtaining the best results from the heating of steel.

The author is particularly indebted to Professor W. Trinks for his continued inspiration, and to Alan Terrile, Glenn Bigelow, and I. S. Wishoski for their invaluable assistance in the preparation of the manuscript. He also wishes to thank all of the manufacturers of industrial heating furnaces, who without exception have been willing to contribute information and illustrations whenever requested.

The science of heating is yet in a stage of rapid and healthy growth, and the subject will necessarily include controversial questions. The author is aware of this, but nevertheless offers his opinions, with the hope that they may be of assistance in the eventual solution of some of these problems.

M. H. Mawhinney

*Salem, Ohio*
*June, 1945*

# Contents

# Introduction

In a previous book by the author,* the subject of furnaces for the heating of steel was discussed in considerable detail. Since that time, fundamental changes have taken place in the conception of furnace design, which are of sufficient importance and extent to warrant another discussion of the subject in book form.

In 1928 the construction of industrial furnaces had just about earned the right to be dignified as an art (it was not yet sufficiently exact in its methods to be known as a science) after a rapid growth from obscurity to a recognized profession in the short space of about twenty years. The experience of that twenty years was crystallized into a logical understanding of the fundamentals of combustion and heating, and the problem in 1928 seemed to be to apply this new-found knowledge to the conservation of fuels, which were being wasted in enormous quantities by antiquated furnace equipment.

As we examine the situation again at this time we can see that this problem of fuels has not been solved in the intervening period. Shortly after 1928 a new understanding of the value of atmospheric control was originated, and the development of this field has occupied the furnace builder, almost to the exclusion of everything else, since that time. This development of atmospheric control in all kinds of open furnaces, and clean and bright-heating in indirectly heated furnaces, have been responsible for the continued adoption of improved and more efficient furnaces. This in itself has saved a great deal of fuel, but at the same time it has created a new fuel problem.

This problem is the conservation of form-value fuels (fuels which can be burned in small quantities and accurately controlled) which are required for atmosphere heating, and which have been used by industry in tremendous quantities for rough heating processes because they were available at low cost. The indications are that the supply of the best of these fuels will approach exhaustion at a rapid rate under these conditions, and that continued use of such fuels where advantage is not taken of their inherently valuable characteristics will only complicate the problems of the near future. Atmosphere heating has come to stay, because it saves both metal and fuel in finishing processes, and gas and electricity will probably remain the only sources of heat capable of accomplishing the desired results.

* "Practical Industrial Furnace Design," John Wiley and Sons, New York, 1928.

In 1928 the problem was to save fuel resources by the extensive use of newly developed, efficient furnaces, which incidentally improved the surface of the metal by providing a better atmosphere. Now, the problem is to control the atmosphere in the furnace to a higher degree of accuracy, which incidentally saves fuel. The only ways to conserve the form-value fuels for this purpose are either the use of coal, producer gas, and heavy fuel oil for rough heating wherever possible, or the development of clean gaseous fuels at low cost from coal and oil.

Very little advantage has been taken of the knowledge developed in the European countries where fuel has been a major problem for many years, and where, as a result, the combustion and use of coal have been developed to a much greater extent than in the United States. Coal-fired furnaces incorporating a built-in gas producer as a part of the furnace are commonly used in the manufacture of Swedish steels which are as good as our own steels in quality; and the same thing has been true in Germany. Also, the manufacture of artificial gases from coal is more extensive and better developed in England and in other countries than it is here. A great deal can be learned about the probable future of American fuel engineering by an examination of the European practices, because it is probable that our conditions will approach theirs as time passes.

The development of automatically controlled coal stokers, which in the underfired form are in reality small built-in producers, is a field of excellent opportunity for the fuel engineer in metallurgical heating, because it is a method of utilizing coal for the heating of steel for hammering, rolling, and similar purposes, with good control of both temperature and atmosphere. Similarly, pulverized coal is a possible substitute for more refined fuels in the heating processes required for the forming of metal, and the development of better equipment for its use will be one of the outstanding results of the present war. Still another possibility is colloidal fuel, made from a mixture of pulverized coal and fuel oil.

In the steel industry, the tendency has continued to be in the direction of heat-treating the finished steel before shipment, and a great development has taken place in the adoption of modern furnaces for this purpose. Metallurgical requirements have become increasingly difficult to meet, and the growth of atmosphere furnaces to produce a clean heated surface and to control the carbon content of the steel during heating has resulted from these metallurgical demands.

The effects of this improvement in metallurgy, with the resulting necessity for better furnaces, has been felt in all branches of steel manufacture. Open hearths and soaking pits have been reexamined and revised in the light of new knowledge of the effects of atmosphere on hot steel. Billet-heating furnaces have been found wanting, because of excessive drafts and absence of control, and have been replaced by controlled equipment.

Heat-treating, much of which is now done by the maker rather than by the purchaser of steel, is being performed in modern equipment which incorporates indirect heating, gas protection, refractory insulation linings, alloy conveyors, and many other improvements. Bright-annealing furnaces are being installed for all manner of steel products, and generators for the manufacture of protective gases are improved almost daily.

A careful review of this progress of the last twenty years, in order to consolidate the acquired knowledge as an assistance in pushing on into the future, is the purpose of this book. The following principal divisions constitute the subject matter.

**Chemical Effects of Heating Steel**

The chemical effects of heating steel certainly constitute one of the principal subjects for discussion in the steel industry today, and must be understood at least to the limits of present knowledge, before considering ways and means of controlling these effects. A chapter is therefore devoted to a discussion of oxidation, carburization, and decarburization of steel when heated under various conditions.

Until about 1930, the oxidation, or scaling, of steel was accepted as a necessary accompaniment of heating, and a considerable amount of loss was allowed for metal converted to mill scale, or oxidized iron. It is true that improvements in furnaces and combustion control had considerably reduced the amount of scale; but with the best control it was recognized that elimination of scale was impossible in open furnaces. About 1930, original research at several different places developed the fact that certain protective gases would prevent the oxidation of steel under certain conditions, and methods were developed for making these gases. Also, furnaces of the electric- and radiant-tube type were built to use them.

In the meantime, necessity for the control of surface carbon was increasing, and it was realized that oxidation had been responsible for holding the depth of carbon variation within the limits allowable to that time. With the elimination of scale, surface carbon control immediately became very important, and the question of protective gases neutral to carbon as well as to iron occupied a place of interest and importance. As will be shown, the resulting research has had far-reaching consequences in the design of furnaces.

**Fuels and Burner Equipment**

The development of improved burners for the combustion of fuel has kept pace with that of atmosphere control, and has reached a point where burners are available for practically every requirement. The second chapter reviews the characteristics of the various fuels and describes the various types of burners available for preparing these fuels for combustion.

Improved methods for the rapid determination of fuel requirements in furnaces and data on the cost comparison of fuels are included in this chapter, together with a discussion of the relative advantages of the various fuels for various requirements.

### Heat Distribution and Furnace Control

Chapter 3 discusses the uniform distribution of heat within the furnace, with the factors which affect this distribution. The importance of heat distribution is due to the necessity for close control of physical characteristics obtained by the heating of steel, and the control of temperature is a corollary of the distribution of temperature.

The control of atmosphere in open furnaces involves the regulation of furnace pressure and fuel-air ratio; to accomplish the control of these factors, together with the control of temperature, every resource of the mechanical and electrical field has been called upon. The result is a most confusing variety of control instruments. To assist in an understanding of this formidable array of control equipment, the many types are described in this chapter.

### Heat Transfer and Fuel Economy

The transfer of heat in a furnace is governed by very complicated laws of heat transfer, which it is not the purpose of this book to discuss. However, empirical methods have been developed by the author and by others for easily calculating heat transfer in industrial furnaces, which are based upon the physical laws but which have been simplified to a curve or simplified chart. Such data have been collected and discussed in this chapter. These include the transfer of heat to metal in the furnace, radiation through openings, and the like.

The distribution of fuels in a typical steel mill is an interesting subject and is discussed to some extent in this chapter, with tabulated summaries for several mills.

### The Quenching of Steel

The quenching of steel after heating is an integral part of the metallurgical practice of heat-treating, but for some reason its practical phases have been almost entirely neglected in the technical literature. For that reason it has been included in this book as the subject of Chapter 5, at the risk of some criticism that it is not truly a heating problem. It can be argued that the quench tank is no more a part of the furnace than is a hammer, press, or other machinery served by furnaces. The difference is that in these cases, the machinery is an engineering subject in itself, with the furnaces as supplementary requirements. In the quenching

process the quench tank is supplementary to the furnace, and is an orphan as far as engineering literature is concerned.

A brief outline of the theory of quenching, prepared with the assistance of Alan P. Terrile, Crucible Steel Co. of America, is followed by a discussion of quenching media and the quantities, circulation, cooling, and control of the various media employed. The chapter is completed with a comprehensive description of the many forms of tanks and machines which have been developed for quenching various steel products.

## Alloys and Refractories

Although the purpose of this volume is not to study the design of furnace structures, an understanding of the significant developments in materials used is of great value to anyone concerned with furnaces in any way. All too often it is found that refractory insulating bricks, originated for inner linings in the last fifteen years, are confused with ordinary insulating bricks and used for the insulation of the outside of firebrick walls, and many similar mistakes are made from lack of knowledge of the fundamentals on which progress has been based. Suspended refractory designs have been worked out to answer certain difficult refractory problems, and a discussion of these designs is included.

Alloy design has made considerable progress in the last twenty years, and descriptions and data on their use in conveyors and other applications are the principal subject of this chapter.

## Steel Mill Furnaces

In Chapter 7, the steel industry is divided into four groups, on the basis of the form of the finished product, as follows: bars, rods and wire, pipe and tubes, and sheets and strip. For each group a survey is then made of the furnaces involved in the successive steps of the manufacture, from ingots to the finished product. At each step, the types of furnaces available are discussed. Such a bird's-eye view of the heating equipment used by the steel industry is of value in summarizing the problems of the preceding chapters and in showing the application of the solutions to actual practice.

# Chapter 1

## Chemical Effects of Heating Steel

Two of the most important considerations in modern steel making are oxidation and decarburization of steel when heated for the various steps in its manufacture. Oxidation, or scaling, is the combination of oxygen with the iron content of the steel, to form one or more of the several forms of iron oxide, or scale. Decarburization of steel may be defined simply as the loss of carbon from the surface, as the result of reaction with the hot gases surrounding the steel during the heating and cooling. But from that point, the question is anything but simple. The large number of complicating factors which affect the carbon loss have so far prevented the compilation of sufficiently complete data for a comprehensive knowledge of the subject, and the development of positive control of the difficulty is still in the stage where available information is scattered and confusing.

In view of this situation, the best plan is to assemble what evidence is available on the subject and to apply it to an outline of the more important heating processes of the steel industry, particularly as a guide to the form in which additional data may be assembled to make it comparative, and consequently more useful.

Laboratory research has established the fact that certain gases are definitely decarburizing to steel, that others are recarburizing (addition of carbon to the surface) in their action, and that still others are practically neutral to steel at elevated temperatures. Progress has also been made in determining the stability of various gas combinations in contact with heated steel of various analyses, but much more remains to be done in this field.

With some definite information available, the next step is the practical application, and it is in this phase that the writer is particularly interested. Until recently, all furnaces were open-fired and the factor of oxidation could be counted upon to assist in the reduction of decarburization, by actually removing the decarburized surface in the form of scale. Now there is an important number of clean and bright-heating furnaces utilizing a protective atmosphere to prevent oxidation of the iron. This has been developed with comparative ease, but the difficulty has been an increased residual decarburization of many steels; and this, together with more rigid specifications, has constituted a new major problem for the makers and users of steel.

In discussing the problem the logical plan is to consider the open furnace and the protective atmosphere furnace separately. This method will be adhered to in the following discussion.

## Open-Fired Furnaces

**Oxidation.** Open furnaces are those in which the flue gases resulting from the combustion of the fuel are in direct contact with the steel during heating and possibly during cooling. For the entire range of fuels these flue gases consist of varying percentages of carbon dioxide, water vapor, and nitrogen, when the theoretical amount of air is supplied and perfectly mixed with the fuel. In practice, the atmosphere also contains either oxygen from an excessive supply of air, carbon monoxide and hydrogen resulting from a deficiency of air, or all of these gases resulting from a poor mixture of air and fuel. An atmosphere containing an excess of air is known as "lean" or "oxidizing," which is correct; an atmosphere having a deficiency of air is commonly called "rich" or "reducing," which is not correct, because in contact with steel the usual rich atmosphere will dissociate to release oxygen to oxidize the steel.

An investigation by W. E. Jominy and D. W. Murphy has established the relation between the atmosphere in open furnaces and the oxidation, or scaling, of many steels. Using city gas at furnace temperatures of about 2000 deg F, they have shown that up to 6 per cent CO in the flue gases (about 77 per cent of theoretical combustion air) the reduction of scale formed in the furnace was not noticeable. From that point to 12 per cent CO in the flue gases (63 per cent complete combustion) there is a gradual reduction in scale formation, and from there to 16.5 per cent CO (55 per cent of theoretical air) the scale formation drops rapidly to practically zero. For practical purposes then, scale cannot be controlled to any important extent, because beyond 6 per cent CO (7.7 to 1.0 air to gas ratio for natural gas) temperature cannot be satisfactorily maintained in an open furnace.

The same investigation by Jominy and Murphy has also contributed information on the effect of temperature and steel analysis upon oxidation, which is of value in a study of decarburization. Their tests have shown that for SAE 1015 steel heated in the usual "neutral" atmosphere of a furnace fired by city gas, the loss of weight per 100 sq in of exposed steel is about as follows:

| mp (°F) | Loss (lb in 40 min) |
|---|---|
| 2000 | 0.09 |
| 2100 | 0.13 |
| 2200 | 0.18 |
| 2300 | 0.23 |
| 2400 | 0.32 |

For the same neutral atmosphere and a common temperature of 2300 deg F, the relative scaling rate for several standard steels as indicated by the loss in weight per 100 sq in of exposed surface is:

| Steel | Loss (lb in 40 min) |
|---|---|
| SAE 1030 | 0.32 |
| SAE 1050 | 0.29 |
| SAE 1015 | 0.24 |
| SAE 1090 | 0.19 |
| High speed | 0.38 |
| SAE 4140 | 0.27 |
| SAE 6145 | 0.26 |
| SAE 3130 | 0.19 |
| SAE 2320 | 0.19 |
| SAE 4615 | 0.18 |

The most important factors which affect the formation of scale in an open furnace include:

(1) **Time at temperature.**

(2) **Furnace pressure,** which determines whether or not free air is drawn into the furnace and in what quantity. The effect of free air on scaling will be further discussed in the next paragraph, but the importance of control of furnace pressure can be emphasized by the statement that the introduction of 2.0 per cent free oxygen into a "neutral" furnace atmosphere will increase the amount of scale formed from four to five times in a furnace fired by the usual oil or gas fuels.

(3) **The kind of fuel,** which determines the chemical analysis of the furnace atmosphere for any given air-gas ratio. Including free air drawn into the furnace by draft, the usual order of scaling activity of the gaseous components of a furnace atmosphere, in order of activity starting with the most active, is oxygen, free air, water vapor, and carbon dioxide, although this order has been found to vary somewhat over the usual range of furnace temperatures. According to Upthegrove* the scaling effect of oxygen, free air, and water vapor becomes appreciable at 1400 deg F and increases very rapidly above that temperature. The effect of carbon dioxide is still small at 1500 deg F and increases slowly above that temperature. At 1700 deg F, the scaling effect of free air is eleven times as great as that of carbon dioxide. At 1800 deg F, the effects of oxygen, free air, and water vapor become retarded, while the effect of carbon dioxide continues to increase, so that at about 2000 deg F the effects of air and carbon dioxide are almost the same.

Carbon monoxide and hydrogen are reducing agents and are found in the products of combustion resulting from rich mixtures of fuel

* *American Gas Association Monthly* (May, 1933).

and air. In order to be effective in their reducing action, the rati $CO_2/CO$ or the ratio $H_2O/H_2$ must be very small. The experimenta results of Jominy and Murphy referred to at the beginning of thi chapter have shown that for the complete elimination of scaling, thes ratios must be too low to permit practical operation of the furnace.

The effect of sulfur in the combustion gases, whether in the form of sulfur dioxide or hydrogen sulfide, is greatly to increase the rate of scaling of most furnace atmospheres, particularly at the higher temperatures used for rolling and forging. Hydrogen sulfide can exist only in reducing atmospheres and has a lesser effect on the scaling of steel than does sulfur dioxide. The effect of any sulfur gas is negligible at lower temperatures such as are found in annealing operations. The presence of 0.10 per cent of sulfur dioxide in a neutral atmosphere furnace at 1800 deg F has been reported to have as much effect in increasing the scaling of steel as has the presence of 1.0 per cent of free oxygen, so that the bad effects of this impurity are obvious. The influence of usual quantities of sulfur is much less in oxidizing furnace atmospheres than it is in neutral or reducing atmospheres. The relative amounts of sulfur in the various heating fuels are given in Chapter 2.

(4) **The air-gas ratio,** which determines whether the atmosphere resulting from combustion is oxidizing, "neutral," or "reducing."

(5) **The temperature of the steel,** the effect of which has already been discussed.

(6) **Analysis of the steel,** as also previously discussed.

(7) **The type of burner,** because the degree of mixing affects the atmosphere produced, and because the different burner block temperatures obtained with different burners affect the extent of dissociation. Variation and tightness of scale with different burners are recognized, but no correlated data are available.

The above factors are common to all open-fired furnaces and constant efforts are made to control at least some of them in all heating processes. Individual solutions are of necessity developed, and any extensive collection of information is still in an early stage of progress. In addition to these common factors, there are others to be found in special cases, including the use of covers and protective compounds.

The amount of oxidizing gas which comes in contact with the steel in unit of time is obviously important in the results obtained, but cannot be controlled in most cases, since it is a function of the amount of heat required in the furnace. The use of sheet-metal covers (not sealed retorts or boxes) for temperatures below 1800 deg F will deflect a large part of the gases away from the steel; these are effective in reducing scale formation where they can be satisfactorily applied. A number of compounds in which the

steel is dipped or which are applied with a brush are available, and are quite effective in reducing the amount of scale and decarburization. The economical use of such compounds, however, is necessarily limited to special applications or to expensive grades of steel.

The tightness of scale formed on heated steel is a complicated subject about which very few published data are available. The relative tightness of the scale is related to the analysis of the steel, probably to a greater extent than to the analysis of the furnace atmosphere surrounding the steel while it is heated. Soaking of the steel at minimum furnace temperature is of primary importance in obtaining a free scale. In practice, the sudden changing of temperature up or down just before discharging the steel from the furnace is effective in loosening the scale (probably by expansion or contraction of the scale jacket), and this practice can be used to advantage when heating for forging or rolling operations where adherent scale must be avoided.

**Decarburization.** With the foregoing outline of scaling, or oxidation, in mind, the parallel phenomenon of decarburization, or loss of carbon, in open furnaces can now be more intelligently considered. Each reaction is closely associated with and enormously complicated by the other, so that a study of decarburization is impractical without an understanding of scaling. Both reactions are affected by the same factors to varying degrees, and the net decarburization, after removal of scale, is determined by the relative speed of reactions resulting from the combination of factors present in any case.

A repetition of the discussion of these factors as they affect decarburization follows — an outline very similar to that just completed for scaling. The factors in order of their importance include the following:

(1) **The time at temperature** is at least one of the most important factors, because the nature of the reaction is such that it progresses proportionately with the time for which the steel is exposed to the atmosphere while at temperature.

(2) **The amount of mechanical reduction** is involved in most problems of decarburization, because the majority of processes involving high temperatures also involve the mechanical reduction by rolling, drawing, or forging after heating. This reduction of cross-sectional area increases the surface area of the piece of steel and correspondingly decreases the thickness of the decarburized skin formed in the heating furnace. The decarburized depth of finished pieces which have been reduced after heating cannot be properly compared unless correction is made for this increase in surface area in each case.

For example, the area of the sides of a $4 \times 4''$ billet $12''$ long is 192 sq in. If this billet is rolled into a bar of $1''$ diameter, the length

becomes 245 in and the new area of the surface is 768 sq in. The increase in area (or decrease in depth of decarburization) will be 400 per cent. In other words, the depth of decarburization on a 1″ diameter round when rolled from a 4 × 4″ billet will be about one-half as great as on a 2″ diameter round from the same billet, and about one-fourth of that on the billet after heating but before rolling. On low-temperature processes for annealing, hardening, normalizing, etc., the factor of reduction with corresponding increase in surface area is usually not involved.

(3) **The furnace pressure** is important because it has been established that free oxygen from the air (as contrasted with oxygen from combustion) is almost as decarburizing as wet hydrogen, which is the worst offender, and is more active than $CO_2$ in removing carbon from most steels. The difference between this free oxygen in air entering the furnace through doors, cracks, and other openings, and the oxygen resulting from an excess of air supplied through the burners is just one of the many confusing facts related to this subject. The only method of preventing the entrance of this free oxygen is to establish and maintain a pressure in the furnace which is slightly higher than atmospheric pressure. This pressure should be about 0.01 in of water at the lowest point in the furnace, and is maintained by controlling the outlet flues of the furnace to suit variations in the fuel supply. This may be accomplished in some cases by a simple connection between the flue damper and the doors or control valves, but in most cases the automatic furnace pressure-control systems are the best solution.

(4) **The air-fuel ratio** as supplied to the burners in open-fired furnaces has a large effect on the resulting decarburization because it directly affects the analysis of the furnace gases. With the so-called reducing atmosphere resulting from a deficiency of combustion air, a part of the hydrogen of the fuel is oxidized to water and the remainder appears in its original form, with a resulting wet hydrogen which is the most active of all decarburizing combinations. The carbon of the fuel appears as both carburizing CO and decarburizing $CO_2$ at a ratio in most cases that is a decarburizing combination. With an excess of air, all the hydrogen appears as water vapor, which is less active than wet hydrogen, and all the carbon is in the form of $CO_2$. Excess oxygen is also present, which increases the rate of formation of scale. For these reasons it is found that the net decarburization after removal of scale is at a minimum for most steels when the air-fuel ratio is on the slightly oxidizing side (1.0 to 3.0 per cent oxygen in flue gases).

(5) **The kind of fuel burned** affects the decarburization because of the variation in analysis of different fuels. It is known that wet hydrogen and $CO_2$ are the principal decarburizing agents from the fuel; as the

amount of these gases produced per unit of heat in the fuel varies with the different fuels, it follows that the decarburizing tendency will vary with these fuels. Calculations of the quantity of water vapor and $CO_2$ in the flue gases from the perfect combustion of sufficient fuel to release 1,000,000 Btu show the comparisons for different fuels in Table 1. The practical comparisons of fuels will be further discussed under specific examples.

Table 1. Gaseous Products from Perfect Combustion per Million Btu Developed

| Fuel | Water vapor (Cu ft) | Carbon dioxide (Cu ft) |
|---|---|---|
| Blast furnace gas | None | 3080 |
| Coke | None | 2180 |
| Bituminous coal | 685 | 1930 |
| Tar | 712* | 1870 |
| Raw producer gas (bituminous) | 950 | 2050 |
| Anthracite producer gas | 1213 | 1861 |
| Fuel oil | 1295 | 1530 |
| Butane | 1560 | 1248 |
| Natural gas | 2020 | 1120 |
| Coke oven gas | 2230 | 1058 |
| Artificial gas | 2394 | 1048 |

* Steam atomization adds about 133 cu ft of water vapor.

(6) **The temperature of the steel.** In general, the tendency to decarburization increases with temperature, because the reaction between the carbon and the gases of the furnace is increased by increase in temperature. However, the oxidation of iron also increases with temperature and there are cases where a reduced decarburization after removal of scale is found with higher temperatures, because the scaling has been increased to a greater extent than the decarburization. A third phenomenon — the diffusion or migration of carbon from unaffected areas to decarburized areas — also affects the final result, and the effect of temperature on this factor is not as yet well understood.

(7) **The steel analysis,** as will be shown by test results to be discussed, has a great effect on the amount of decarburization under any conditions, which is a further complication because the amount of data necessary for any broad understanding of the subject is enormously increased. It will be a long time before any correlated understanding of the effects of the other factors will be definitely known for the wide range of steels from low-carbon to high-carbon, high-speed, alloy, and stainless steels.

(8) **The type of burner.** Premix burners with thorough mixing and high flame temperatures consistently produce the lowest decarburization in the author's experience, probably because of more complete combustion of the fuel before contacting the steel and because of dissociation of combustion gases by the higher burner-port temperatures.

Similar results are also indicated from furnaces which are designed with hot combustion chambers (indirect-fired furnaces) for the same reasons.

With this outline of the factors involved in the decarburization of steels, and with the simultaneous scaling action to some extent understood, it is now possible to examine more intelligently certain scattered evidence concerning decarburization in different furnaces, which the author has collected over a considerable period of time. The data were obtained in furnaces which may be outlined as follows:

Soaking pits to heat ingots, fired with raw producer gas.
Batch regenerative (reversing) furnaces for billets, fired with raw producer gas, coke-oven gas, and natural gas.
Batch one-way fired furnaces for billets, fired with coke-oven gas, natural gas, coal, and fuel oil.
Continuous pusher furnaces for billets, fired with producer gas and natural gas.
Car-type furnaces for annealing, fired with coke-oven gas and natural gas.
Batch furnaces for annealing, fired with coke.
Certain special furnaces.

## Soaking Pits

Data collected from soaking pits included results from four grades of steel, each heated in a standard regenerative reversing pit with natural

Table 2. Decarburization in Soaking Pits

| Factors (See text) | Regenerative pit, natural draft | | | | Regenerative pit, forced draft | | | |
|---|---|---|---|---|---|---|---|---|
| (1) Fuel | producer gas | | | | producer gas | | | |
| (2) Furnace pressure | 0.01 in water negative | | | | 0.05 in water positive | | | |
| (3) Temperature (deg F) | 2150 to 2335 | | | | 2150 to 2350 | | | |
| (4) Air-gas ratio | oxidizing | | | | slightly oxidizing | | | |
| (5) Type burner | none | | | | none | | | |
| (6) % area increase | 308 | 380 | 550 | 550 | 308 | 380 | 550 | 550 |
| (7) Time in pit (hrs) | 6.9 | 9.8 | 7.7 | 6.1 | 6.5 | 9.8 | 7.7 | 5.6 |
| (8) Grade steel, SAE | 1010 | 2335 | 9260 | 1065 | 1010 | 2335 | 9260 | 1065 |
| Decarburization (in) (microscope) | | | | | | | | |
| Carbonless | 0.000 | 0.000 | 0.000 | 0.011 | 0.002 | 0.000 | 0.000 | 0.002 |
| Pronounced | 0.010 | 0.017 | 0.027 | 0.007 | 0.008 | 0.010 | 0.006 | 0.003 |
| Slight | 0.010 | 0.013 | 0.014 | 0.007 | 0.010 | 0.010 | 0.010 | 0.005 |
| Actual total depth | 0.020 | 0.030 | 0.041 | 0.025 | 0.020 | 0.020 | 0.016 | 0.010 |
| Total depth corrected to 300% area increase | 0.021 | 0.038 | 0.075 | 0.046 | 0.021 | 0.025 | 0.029 | 0.018 |
| Remarks | | | | | | | | |
| Ingot size (in) | 23 | 23 | 22 | 22 | 23 | 23 | 22 | 22 |
| Billet size (in) | 8×7 | 6×6 | 4×4 | 4×4 | 8×7 | 6×6 | 4×4 | 4×4 |
| All cherry or red ingots when charged. | | | | | | | | |

draft, and in an identical pit except for the provision of forced draft from a low-pressure fan, which made it possible to maintain a slight positive pressure in the pit at all times. The fuel was producer gas in all cases, and all the results tabulated in Table 2 were checked by several additional tests.

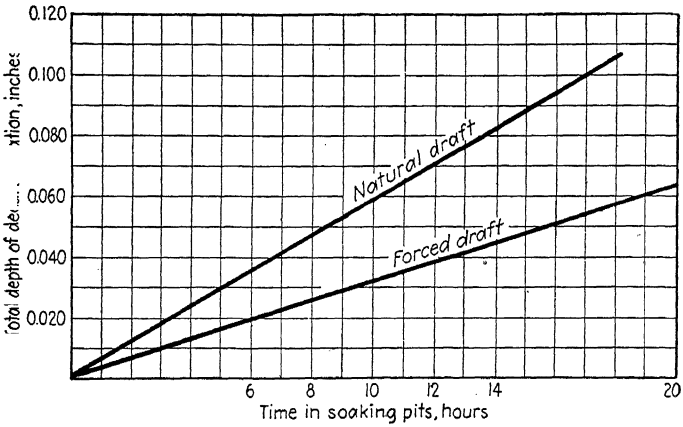


Figure 1. Graphical presentation of the data shown in Table 2 on decarburization in soaking pits. Note that the decarburization is corrected to a 300 per cent area increase. The improved results obtained can be accounted for only by the improved control of furnace atmosphere with forced draft.

The figures of Table 2 indicate the very considerable effect of the furnace pressure in preventing the infiltration of free air into the furnace. All other factors remained the same in each case, and the improved results in decarburization can be accounted for only by the improved control of furnace atmosphere with forced draft. Figure 1 shows the data of Table 2 in graphical form.

## Batch Regenerative Furnaces

The decarburization figures obtained for batch regenerative furnaces are similar to those for the soaking pits except that in this case the opportunity was available to compare the effects of different fuels as well as the effects resulting from furnace pressure. All results given in Table 3 and Table 4 are the average of many consistent tests. Table 3 shows the decarburization obtained in regenerative reversing batch type furnaces with natural draft and consequent necessity for negative pressure at the hearth, while Table 4 is for the same furnace with forced draft and positive pressure in the furnace.

One conclusion from a study of these tables is that the decarburization resulting from a furnace with positive pressure is considerably less than that resulting from a furnace under negative pressure, all other factors

## Table 3. Decarburization in Regenerative Batch Furnaces, Natural Draft

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Factors (See text) | | | | | | | | | | | | | | | |
| (1) Fuel | producer gas | coke oven gas | | | | | | | | | | | | | |
| (2) Furnace pressure | − 0.01 | − 0.01 in water | | | | | | | | | | | | | |
| (3) Temperature (deg F) | 2300 | 2300, approximately | | | | | | | | | | | | | |
| (4) Air-gas ratio | oxidizing | oxidizing | | | | | | | | | | | | | |
| (5) Burners | none | none | | | | | | | | | | | | | |
| (6) % area increase | 235 | 286 | 400 | 246 | 246 | 246 | 305 | 267 | 267 | 267 | 400 | 400 | 400 | 320 | 320 |
| (7) Time in furnace (min) | 235 | 105 | 120 | 95 | 103 | 64 | 90 | 94 | 64 | 68 | 135 | 120 | 162 | 132 | 130 |
| (8) Grade steel, SAE | 1020 | 1335 | 1340 | 1340 | 1340 | 1340 | 1340 | 1340 | 1340 | 1340 | 1020 | 1020 | 1020 | 3140 | 3140 |
| Decarburization, $\frac{(in)}{1000}$ (micro cope) | | | | | | | | | | | | | | | |
| Complete | 5 to 10 | — | — | 0 to 2 | — | 0 to 3 | — | 2 to 5 | — | 0 to 3 | 2 to 5 | 2 to 5 | 3 to 6 | — | — |
| Pronounced | 20 to 25 | 8 to 25 | 6 to 10 | 10 to 16 | 10 to 20 | 7 to 12 | 4 to 12 | 10 to 18 | 3 to 12 | 12 to 18 | 12 to 18 | 8 to 15 | 10 to 15 | 12 to 20 | 12 to 18 |
| Slight | — | 7 to 12 | 6 to 20 | 15 to 20 | 10 to 15 | 5 to 8 | 8 to 22 | 15 to 20 | 7 to 18 | 10 to 20 | 10 to 15 | 10 to 15 | 15 to 25 | 8 to 15 | 8 to 12 |
| Actual total depth | 25 to 35 | 15 to 37 | 12 to 30 | 25 to 35 | 20 to 35 | 15 to 20 | 12 to 34 | 25 to 35 | 10 to 30 | 20 to 35 | 25 to 35 | 20 to 30 | 25 to 40 | 20 to 35 | 20 to 30 |
| Total depth, corrected to % area increase | 28 | 35 | 40 | 28.7 | 28.7 | 16.4 | 34.5 | 31.2 | 26.8 | 31.2 | 44.8 | 40 | 53.5 | 37.3 | 32 |
| Remarks | | | | | | | | | | | | | | | |
| Heated size (in) | 8 × 7 | 5 × 5 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 |
| Finished size (in diameter) | 3⅛ | 1¾ | 1 | | | 1⅝ | 1 5/16 | 1½ | 1½ | 1½ | 3 1/32 | 3 1/32 | 1 1/32 | 1.57 | 1.57 |

## Table 4. Decarburization in Regenerative Furnaces, Forced Draft

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Factors (See text)** | | | | | | | | | | | | | | | | | | | | | |
| (1) Fuel | coke oven gas | | | | | | | | | | | | natural gas | | | | | | | | |
| (2) Furnace pressure | 0.02 to 0.05 in water, positive pressure | | | | | | | | | | | | 0.02 to 0.05 in water, positive pressure | | | | | | | | |
| (3) Temperature (deg F) | 2300, approximately | | | | | | | | | | | | 2300, approximately | | | | | | | | |
| (4) Air-gas ratio | slightly oxidizing | | | | | | | | | | | | slightly oxidizing | | | | | | | | |
| (5) Burners | none | | | | | | | | | | | | none | | | | | | | | |
| (6) % area increase | 208 | 228 | 228 | 228 | 228 | 249 | 236 | 572 | 208 | 458 | 208 | 320 | 267 | 267 | 267 | 281 | 281 | 281 | 264 | 332 | 410 |
| (7) Time in furnace (min) | 100 | 74 | 67 | 60 | 70 | 85 | 98 | 110 | 100 | 120 | 150 | 92 | 145 | 107 | 115 | 78 | 108 | 125 | 139 | 80 | 135 |
| (8) Grade steel, SAE | 1050 | 1345 | 1345 | 1345 | 1080 | 4120 | 1045 | 1030 | 1050 | 3140 | 1050 | 1095 | 5130 | 5130 | 5130 | 9260 | 9260 | 9260 | 4140 | 3140 | 1095 |
| **Decarburization $\frac{(in)}{1000}$ (microscope)** | | | | | | | | | | | | | | | | | | | | | |
| Complete | 0 to 4 | — | — | — | 0 to 1 | — | 1 to 2 | — | 1 to 3 | — | 0 to 2 | — | 0 to 2 | — | — | — | — | — | 0 to 2 | — | — |
| Pronounced | 9 to 16 | 8 to 13 | 0 to 8 | 4 to 10 | 8 to 12 | — | 10 to 17 | 2 to 3 | 8 to 12 | 4 to 6 | 12 to 15 | 4 to 7 | 15 to 25 | 5 to 12 | 10 to 20 | 6 to 10 | 3 to 10 | 3 to 8 | 7 to 12 | 0 to 6 | 5 to 7 |
| Slight | 9 to 12 | 8 to 10 | 5 to 15 | 6 to 10 | 4 to 6 | 15 to 30 | 15 to 18 | 4 to 6 | 7 to 12 | 4 to 6 | 12 to 18 | 2 to 4 | 8 to 12 | 9 to 12 | 5 to 12 | 6 to 12 | 6 to 16 | 5 to 10 | 4 to 7 | 5 to 8 | 2 to 4 |
| Actual total depth | 18 to 28 | 16 to 23 | 5 to 23 | 10 to 20 | 12 to 18 | 15 to 30 | 23 to 35 | 6 to 9 | 15 to 25 | 8 to 12 | 25 to 35 | 6 to 11 | 25 to 35 | 14 to 24 | 15 to 30 | 15 to 22 | 9 to 26 | 8 to 18 | 12 to 18 | 5 to 14 | 7 to 11 |
| Total depth, corrected to 300% area increase | 19.5 | 17.5 | 17.5 | 15.2 | 13.7 | 25.0 | 27.6 | 17.2 | 17.5 | 18.2 | 24.5 | 11.6 | 31.2 | 20.8 | 22.7 | 20.6 | 20.4 | 16.8 | 15.8 | 15.6 | 15.1 |
| **Remarks** | | | | | | | | | | | | | | | | | | | | | |
| Heated size (in) | 6 × 6 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 5 × 5 | 5 × 5 | 5 × 5 | 6 × 6 | 4 × 4 | 6 × 6 | 4 × 4 | 5 × 5 | 5 × 5 | 5 × 5 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 5 × 5 | 5 × 5 |
| Finished size (in diameter) | 2⅞ | 1¾ | 1¾ | 1¾ | 1¾ | 2 1/16 | 2⅛ | ⅞ | 2⅞ | ⅞ | 2⅞ | 1 7/32 | 1⅞ | 1⅞ | 1⅞ | 1 27/64 | 1 27/64 | 1 27/64 | 1 33/64 | 1 33/64 | 1 7/32 |

being identical. Also, for a furnace with negative pressure but fired with producer gas, the decarburization is less than that resulting from either coke-oven or natural gas, which is in agreement with the relative amounts of water vapor resulting from the complete combustion of these fuels, as shown in Table 1. Finally, natural gas shows relatively little advantage over coke-oven gas under similar conditions, which is again in agreement with the water vapor figures of Table 1. Figure 2 shows the results graphically for the regenerative furnaces.

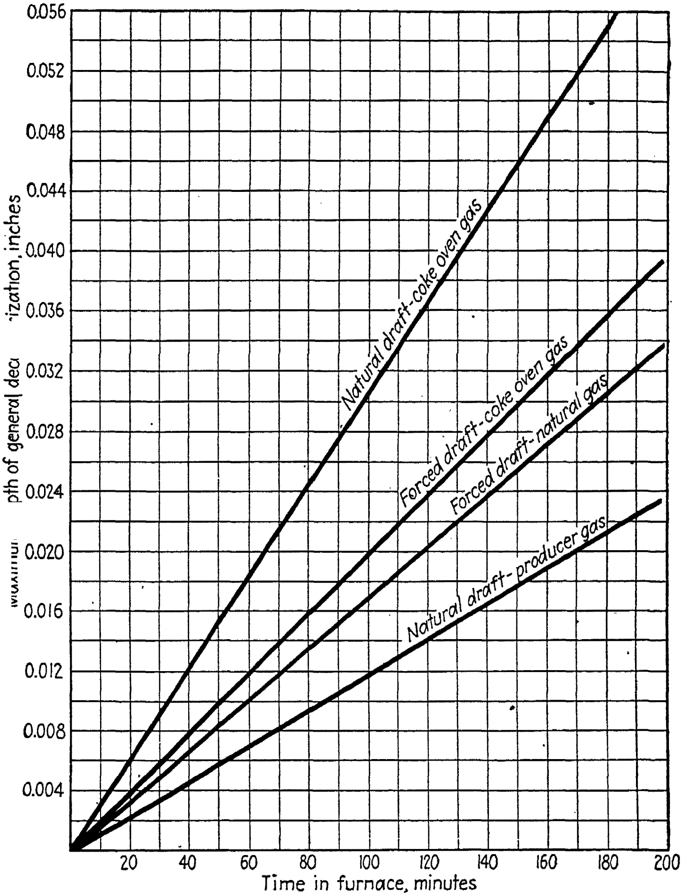


Figure 2. Decarburization in regenerative furnaces. Decarburization is corrected to 300 per cent area increase.

## One Way-Fired Batch Furnaces

These furnaces are similar to the regenerative furnaces of the preceding section, in that they are of the batch type with several doors along the front and that they are used for the same purpose; but they differ in that

they are fired from the ends with burners utilizing cold air for combustion. The use of burners provides a better mixing of fuel and air than is possible in the reversing furnace, where the air enters the furnace from the regenerator and mixes with the fuel inside the furnace itself. Also, the temperature in the burner ports is higher than at any point in the furnace without burners, which affects dissociation of the gaseous products of combustion, as has already been described. Table 5 has been prepared to show the comparative results from furnaces of this type, fired by several different fuels and heating a variety of steels.

The results are shown graphically in Figure 3, and a comparison with Figure 2 will show that the decarburization resulting in burner-fired furnaces is somewhat less than in the reversing furnaces. This and other experiences

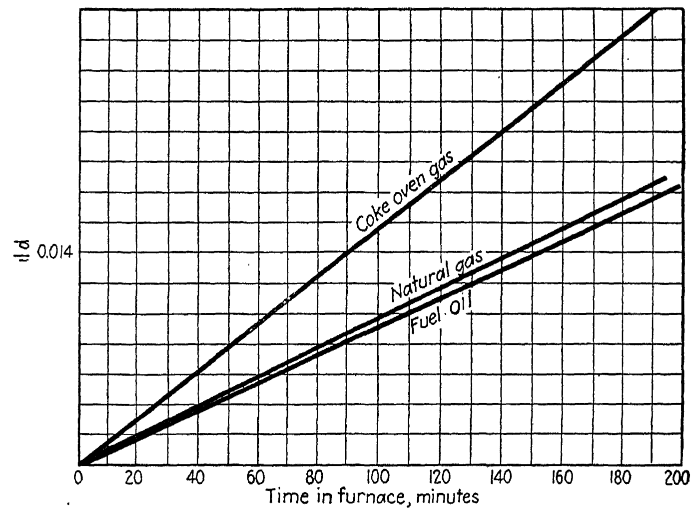


Figure 3. Decarburization in burner-fired furnaces. Decarburization corrected to 300 per cent area increase.

point to the conclusion that minimum decarburization results when combustion of any fuel is as complete as possible before the products of combustion come in contact with the heating steel. Figure 3 also supports the previous statement that the fuels highest in hydrogen cause the greatest amount of decarburization. In this case, fuel oil, natural gas, and coke-oven gas cause increasing decarburization, in the order named.

In the case of high-speed tool steels, the decarburization is difficult to measure by microscopic examination and can be compared only by analysis of turnings from a rolled bar. One method is to discard the outside 0.025 in (0.0125 in from surface) from the diameter of the bar and to analyze the next 0.025 in from the diameter for carbon, which analysis can be

Table 5. Decarburization in Burner-Fired Batch Furnaces

| Factors (See text) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) Fuel | coke oven gas | | | | | | | fuel oil | | | | | natural gas |
| (2) Furnace pressure | 0.02 to 0.05 in water, positive | | | | | | | 0.02 to 0.05 in water, positive | | | | | 0.02 to 0.05 in |
| (3) Temperature (deg F) | 2300, approximately | | | | | | | 2100, approximately | | | | | 2300 |
| (4) Air-gas ratio | slightly oxidizing | | | | | | | slightly oxidizing | | | | | slightly oxidizing |
| (5) Burners | luminous flame type | | | | | | | low pressure oil burners | | | | | luminous |
| (6) % area increase | 286 | 400 | 246 | 246 | 267 | 267 | 320 | 572 | 480 | 545 | 1700 | 545 | 267 |
| (7) Time in furnace (min) | 100 | 120 | 105 | 65 | 91 | 60 | 94 | 150 | 90 | 210 | 150 | 135 | 70 |
| (8) Grade steel, SAE | 1335 | 1340 | 1340 | 1340 | 1340 | 1340 | 1095 | 52100 | 52100 | 1085 | 1075 | Nitralloy | 52100 |
| Decarburization $\frac{(\text{in})}{1000}$ (microscope) | | | | | | | | | | | | | |
| Complete | — | — | — | 0 to 1 | — | 0 to 2 | — | — | — | — | — | 0 to 3 | — |
| Pronounced | 2 to 5 | 1 to 4 | 10 to 20 | 5 to 8 | 1 to 5 | 7 to 12 | 3 to 6 | 0 to 2 | 2 | 6 to 10 | 3 to 5 | 2 to 10 | — |
| Slight | 2 to 3 | 4 to 8 | 10 to 15 | 4 to 7 | 8 to 15 | 3 to 5 | 3 to 4 | — | — | — | — | — | 4 to 7 |
| Actual total depth | 5 to 8 | 5 to 12 | 20 to 35 | 9 to 15 | 9 to 14 | 8 to 15 | 6 to 10 | 0 to 2 | 2 | 6 to 10 | 3 to 5 | 2 to 13 | 4 to 7 |
| Total depth, corrected to 300% area increase | 7.7 | 15.0 | 28.7 | 12.3 | 12.5 | 13.3 | 10.6 | 3.8 | 3.2 | 14.6 | 22.6 | 14.6 | 6.3 |
| Remarks | | | | | | | | | | | | | |
| Heated size (in) | 5 × 5 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | 4 × 4 | $3\frac{3}{4}$ sq | $3\frac{3}{4}$ | $3\frac{3}{4}$ | $3\frac{3}{4}$ | $3\frac{3}{4}$ | 4 × 4 |
| Finished size (in diameter) | $1\frac{3}{4}$ | 1 | $1\frac{5}{8}$ | $1\frac{5}{8}$ | $1\frac{1}{2}$ | $1\frac{1}{2}$ | $1\frac{7}{32}$ | $\frac{21}{32}$ | $\frac{25}{32}$ | $\frac{11}{16}$ | .220 | $\frac{11}{16}$ | $1\frac{1}{2}$ |

compared with drillings from the center of the bar. The average of many tests by this method shows that the drop in carbon after heating 0.72 per cent carbon steel to about 2100 deg F in a coal-fired furnace and rolling from a 2 in square billet to a 1 in diameter round (200 per cent increase in surface area) is from 1 to 2 points of carbon (1 point is 0.01 per cent). The same drop with natural gas and a reducing atmosphere is from 7 to 10 points; and with natural gas and an oxidizing atmosphere with positive furnace pressure it is from 2 to 5 points.

Table 6 gives the details of typical tests selected from a large number of tests on Rex AA tool steel heated in coal-fired furnaces, in natural gas-fired

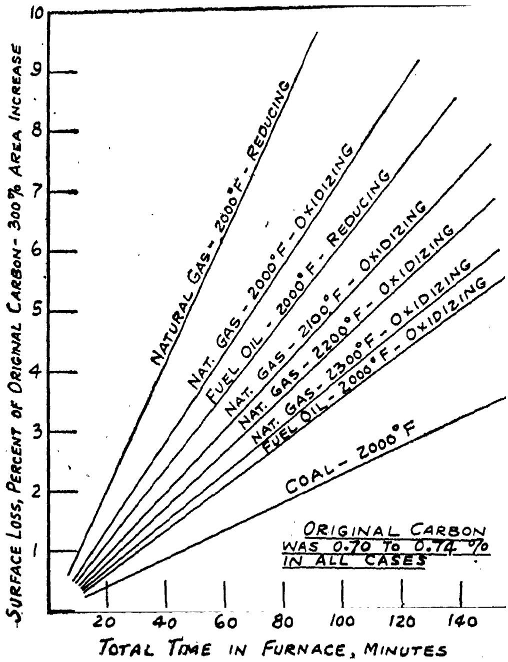


Figure 4. Comparative decarburization of tool steel under different conditions and determined by analysis of turnings.

furnaces, and in oil-fired furnaces under different conditions of temperature and time. The gas- and oil-fired furnaces were fired from the ends with blast-type burners, and a furnace pressure was maintained in the furnace at all times. Figure 4 shows the same information in graphical form and was made up from the results of 50 tests. The loss in carbon in this chart is expressed in per cent of original carbon content, which was from 0.70 to 0.74 per cent carbon in all cases.

The interesting feature in this case is the fact that the decarburization is progressively reduced with increase in the temperature of the gas-fired furnace, which may be accounted for by a more rapid increase in scaling

## Table 6. Decarburization of Tool Steel

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Factors (See text)** | | | | | | | | | | | | | | | |
| (1) Fuel | coal | | | | natural gas | | | | | | | | | fuel oil | |
| (2) Furnace pressure | variable | | | | .02 in water | | | | | | | | | .02 in water | |
| (3) Temperature | 1900 | 2000 | 1950 | 2050 | 2000 | 2000 | 2000 | 2100 | 2100 | 2200 | 2200 | 2300 | 2300 | 2000 | 2000 |
| (4) Air-gas ratio | —— | | | | 2.0% oxygen | | | | | | | | | 2.0% oxygen | reducing, 2% CO |
| (5) Burners | —— | | | | blast type | | | | | | | | | low pressure | low pressure |
| (6) % area increase | 155 | 155 | 145 | 150 | 142 | 138 | 155 | 144 | 155 | 150 | 127 | 145 | 200 | 200 | 200 |
| (7) Time in furnace (min) | 100 | 90 | 120 | 110 | 90 | 90 | 120 | 100 | 60 | 120 | 140 | 80 | 110 | 90 | 90 |
| (8) Grade steel | Rex AA tool steel | | | | Rex AA tool steel | | | | | | | | | Rex AA tool steel | |
| **Decarburization** | | | | | | | | | | | | | | | |
| Analysis, % carbon × 100 before heating | 72.4 | 72.4 | 71.8 | 73.0 | 72.9 | 73.3 | 73.2 | 71.0 | 71.8 | 72.6 | 73.3 | 74.0 | 71.7 | 72.5 | 73.0 |
| Analysis, % carbon × 100 after heating * | 69.6 | 68.9 | 67.4 | 70.1 | 59.1 | 62.0 | 60.8 | 62.6 | 66.9 | 64.9 | 61.0 | 70.2 | 67.5 | 69.0 | 67.0 |
| Loss, % carbon × 100 by analysis | 2.8 | 3.5 | 4.4 | 2.9 | 13.8 | 11.3 | 12.4 | 8.4 | 4.9 | 7.7 | 12.3 | 3.8 | 4.2 | 3.5 | 6.0 |
| Loss, % original carbon × 100 | 3.9 | 4.8 | 6.1 | 4.0 | 18.9 | 15.4 | 16.9 | 11.8 | 6.8 | 10.6 | 16.8 | 5.2 | 5.8 | 4.8 | 8.2 |
| Loss, % carbon × 100 corrected to 300% area increase in rolling | 2.0 | 2.5 | 3.0 | 2.0 | 9.0 | 7.0 | 8.5 | 5.6 | 3.6 | 5.3 | 7.0 | 2.5 | 4.5 | 3.2 | 5.5 |
| **Remarks** | | | | | | | | | | | | | | | |
| Heated size (in sq) | 1¾ | 1¾ | 2 | 2¼ | 2¾ | 2¾ | 1¾ | 3½ | 1¾ | 2¼ | 3½ | 2 | 1½ | 2 | 2 |
| Finished size (in diameter) | 1.13 | 1.13 | 1.38 | 1.50 | 1.94 | 2.0 | 1.13 | 2.44 | 1.13 | 1.50 | 2.75 | 1.38 | 0.75 | 1 | 1 |

* Carbon analysis on billets made from drillings. Carbon analysis on finished bars made by discarding 0.025 in from the diameter and analyzing the next 0.025 in on the diameter.

with increased temperature than in decarburization with the same temperature increase.

A few tests available from gas-fired furnaces of the batch type in which a bridgewall is interposed between the burners and the heating steel indicate that the resulting decarburization from heating in this type of furnace is less than is shown in Figure 4 for the direct-fired type. This is no doubt due to the fact that combustion is completed before the combustion gases come in contact with the steel.

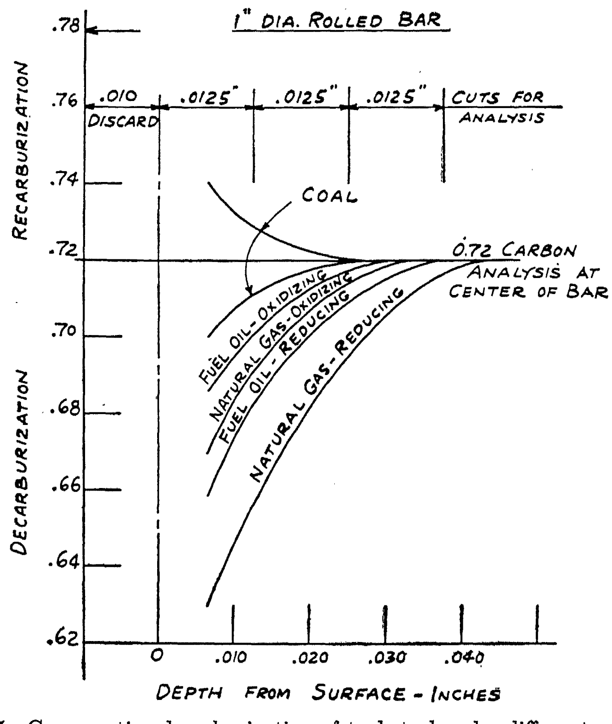


Figure 5. Comparative decarburization of tool steel under different conditions.

Figure 5 shows the relative decarburization of Rex AA tool steel with different fuels in another graphical manner. This illustration shows the decarburization in depth from the surface as obtained by successive cuts for analysis. It is apparent that the decarburization is deeper as well as greater with a reducing atmosphere than it is with an oxidizing atmosphere when heating with either natural gas or fuel oil. In the case of coal it is possible to carburize the steel, as shown, by firing with a deficiency of air, indicated by an excessively smoky condition in the furnace. The use of stokers will greatly improve the consistency of results from coal-fired furnaces.

## Continuous Billet Furnaces

Continuous furnaces for heating billets to rolling temperatures have either end or side discharge, which has a considerable effect on the amount of decarburization obtained. With end discharge, the entrance of free air cannot be prevented and the decarburization is increased in comparison with a side-discharge furnace where positive pressure can be maintained. Figure 6 shows graphically the comparison between the results in an end-discharge furnace fired with producer gas and heating SAE 9260 steel, and in a side-discharge furnace fired with natural gas and equipped with automatic pressure control when heating SAE 1040 steel.

In spite of the fact that producer gas is the better fuel for decarburization, the end discharge furnace shows the greater amount of decarburization. Analysis of the atmosphere immediately surrounding the steel in this case

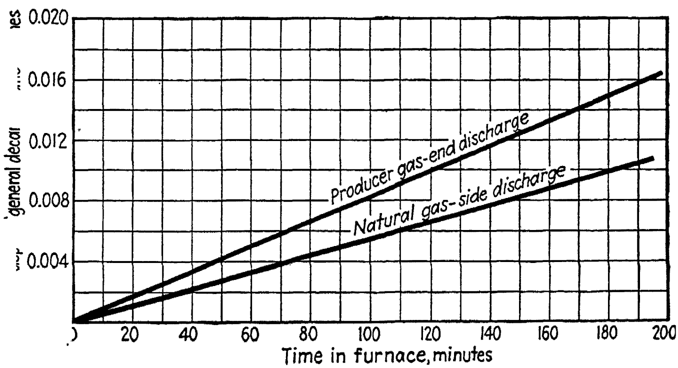


Figure 6. Decarburization in continuous billet furnaces. Decarburization corrected to 300 per cent area increase.

showed 10 to 12 per cent of oxygen as the result of the draft through the furnace. The values of Figure 6 have been corrected to 300 per cent increase in area and can be compared directly with those of Figures 2 and 3. In making such comparisons it should be remembered that in the continuous furnace the time in the furnace is partly spent in passing through a preheating portion of lower temperature before reaching the end of maximum temperature, while in a batch-type furnace the steel is charged directly into a hot furnace in most cases. The continuous furnace is for this reason inherently less decarburizing than the batch-type.

As an indication of the progressive decarburization of steel exposed to furnace atmosphere for an extended time, a test of a bar rolled from an SAE 9260 billet heated for 70 hours in the end-discharge furnace of Figure 6 showed a depth of general decarburization of 0.215 in after correcting to 300 per cent area increase in rolling. This would indicate that over an extended time, the depth of decarburization does not increase in direct

proportion to the time of exposure. Of this total depth of 0.215 in, the outside 0.010 in was carbonless, the next 0.095 in was decarburized to a pronounced degree, and the last 0.110 in was slightly decarburized.

## Annealing Furnaces

In annealing furnaces the temperatures are lower than in the heating furnaces so far discussed, but the time is longer and there is frequently a cooling cycle during which decarburization is likely to be at an increased rate due to air infiltration into the furnace. Also, there is usually no subsequent reduction, with corresponding increase in surface area, to reduce the decarburization of the finished piece. An exception is the process annealing between cold-drawing operations.

Two typical annealed results from similar car-type furnaces are shown in Table 7. In each case, the car-type annealing furnace was equipped with automatic pressure control which maintained a constant positive pressure in the furnace during heating and soaking, and which reduced the infiltration of air to a minimum during the cooling cycle. In the one case, SAE 3140 steel was annealed with coke-oven gas fuel, and in the other case SAE 52100 steel was annealed with natural gas fuel.

Table 7. Decarburizing in Annealing Furnaces

| | Car type furnace | Car type furnace |
|---|---|---|
| Factors | | |
| (1) Fuel | coke oven gas | natural gas |
| (2) Furnace pressure | 0.02 in water, positive | 0.03 in water, positive |
| (3) Temperature (deg F) | 1600 | 1475 |
| (4) Air-gas ratio | slight reducing | slight reducing |
| (5) Burners | low press premix | high press injector |
| (6) % area increase | none | none |
| (7) Time to temperature (hrs) | 11 | 10 |
| Time at temperature (hrs) | 1 | 6 |
| Time cooling to 900 deg F | 22 | 29 |
| Total time (hrs) | 34 | 45 |
| (8) Grade steel, SAE | 3140 | 52100 |
| Decarburization (in) | | |
| Complete | 0.002 to 0.005 | |
| Partial | 0.020 to 0.026 | 0.015 |
| Total depth | 0.022 to 0.031 | 0.015 |
| Remarks | | |
| Weight charged (lbs) | 21,000 | 15,000 |
| Material | bars | tubing |

A few annealing furnaces are still fired with coal or coke in spite of high operating costs, because of the apparent advantages of these fuels in reducing decarburization with open heating. In such furnaces decarburization can result from infiltration of air into the furnace. With the usual

operation, air for combustion during the heating up period is drawn through the coke fire by draft from the stack, so that the heating chamber is under negative pressure and air is drawn in through door cracks and over the hearth. During the cooling cycle the damper is closed and the fire banked, but a draft still exists in the heating chamber. The best cure for this condition is forced draft from a low-pressure fan which must be applied both above and below the fire. With air below the fire only, the heating chamber can be kept under positive pressure during the cooling cycle and decarburization prevented, but during the heating cycle air below the fire only converts the firebed into a gas producer, with the produced gas unable to find air for combustion in the heating chamber when the damper is retarded. Additional air in proper quantities above the fire produces a clean flame in the heating chamber under slight pressure. The relative ratio of air to fuel is not so important in this case, because of the low amount of hydrogen in the fuel.

The surface of a 0.74 carbon tool steel will be decarburized to about 0.70 carbon after annealing in a natural draft coke-fired furnace, and the depth of decarburization will be about 0.015 in from the surface. By proper application of forced draft, this decarburization can be entirely eliminated.

Compounds in the form of paste or liquid, applied to the steel either by dipping or painting, are sometimes used to reduce the amount of decarburization resulting from heating in an open furnace. The results obtained by this process when applied to billets to be heated for rolling are erratic as yet, and the amount of labor involved is considerable. However, there are many examples of successful use of such compounds for the treatment of small parts after machining, and they can be used to advantage on billets of special material which will permit the cost of applying the compound with the necessary amount of care and consistency.

A summary of conditions best suited for minimum decarburization in open-fired furnaces is then as follows:

(1) Time at temperature as short as possible.
(2) Maximum reduction in section by rolling or forming after heating.
(3) Positive pressure in the furnace to exclude air.
(4) Furnace temperature as low as possible in most cases.
(5) Combustion air slightly in excess of requirements for perfect combustion (up to 3.0% $O_2$ in flue gases).
(6) A fuel low in hydrogen content.
(7) Burners with good fuel-air mixing characteristics.

## Protective Atmosphere Furnaces

The use of protective atmosphere for clean and bright-heating began to be a factor in furnace design about 1930 and has made rapid strides since then. The first installations used hydrogen and hydrogen-nitrogen

Table 8. Protective Gas Atmospheres

| Type | Manufacture | Typical analysis $CO_2$ | CO | $O_2$ | $CH_4$ | $H_2$ | $N_2$ | Dewpoint (deg F) | Principal uses |
|---|---|---|---|---|---|---|---|---|---|
| 1. Dissociated ammonia | Dissociation of ammonia by heat, followed in some cases by partial burning and drying | 0.0 | 0.0 | 0.0 | 0.0 | 75.0 to 5.0 | 25.0 to 95.0 | − 60 | For stainless anneal and for long-cycle anneal of high-carbon steel with liquid seals to reduce the consumption; brazing; hardening tool steel in small units |
| 2. Rich hydrocarbon gas, not conditioned. "Rich DX," etc. | Partial combustion with catalyst, average 6 : 1 * air-gas ratio, drying by refrigerator only | 5.5 | 9.0 | 0.0 | 0.8 | 15.0 | 69.7 | + 50 | Clean anneal of low-carbon steel or heat-treating where decarburization is not important; short cycle bright-heating |
| 3. Rich hydrocarbon gas, completely conditioned. "Rich Monogas," NX, etc. | Same as 2, with chemical removal of $CO_2$ and drying in absorption driers | 0.3 max | 9.5 | 0.0 | 0.8 | 15.8 | 73.6 | − 60 | Long-cycle annealing of intermediate carbon steels and heat-treating in large units |
| 4. Lean hydrocarbon gas, completely conditioned. "Lean Monogas," etc. | Same as 3 except that average air-gas ratio is 9 : 1 * | 0.3 max | 2.8 | 0.0 | 0.0 | 3.9 | 93.0 | − 60 | Long-cycle anneal of wide range of carbon and alloy steels |
| 5. Double cracked gas (endothermic) | Partial combustion of hydrocarbon gas (average ratio 4 : 1) with products refrigerated and reheated with addition of raw gas. Again refrigerated | 1.7 | 16.0 | 0.0 | 2.2 | 23.5 | 56.6 | + 50 | Similar to 3 above |
| 6. Endothermic generator gas. "Endo-gas," CG, RX, etc. | Partial combustion of hydrocarbon gas with catalyst in electric generator, average air-gas ratio of 2.5 : 1 | 0.5 | 20.0 | 0.0 | 1.0 | 38.0 | 40.5 | + 50 | Heat-treating (short cycles under 2 hours) of wide range of carbon and alloy steels in small units; brazing |
| 7. "Drycolene" | Complete combustion of hydrocarbon gas, products passed over hot carbon and absorption dried | 0.5 | 20.0 | 0.0 | 0.0 | 0.2 | 79.3 | − 40 | Similar to 6 above |
| 8. Charcoal gas, "Charmo," "Hydrizing," etc. | Air passed over heated carbon | 0.5 | 30.0 | 0.0 | 0.0 | 2.0 | 67.5 | + 50 | Principally heat-treating (short cycle) of high-speed steels and the like, in small units; brazing |
| 9. Lithium vapor | Partially burned hydrocarbon gas (6 : 1 air-gas ratio) mixed with lithium vapor | 8.0 | 6.0 | 0.0 | 0.0 | 9.0 | 77.0 | — | Similar to 8 above |

* Air-gas ratios are for natural gas (6 : 1 is 60% of air required for complete combustion).

mixtures, which are still used for stainless steels and for some high-carbon steel treatments. To reduce the cost of the protective gas, partial combustion of hydrocarbon gases was developed. With the early 6 : 1 air-gas ratio for natural gas and with the proper catalyst in the generator, the protective gas made from partial combustion of natural gas contains about 5 per cent $CO_2$, 9 per cent CO, 15 per cent hydrogen, 1 per cent methane, no oxygen, and considerable water vapor. This water vapor can be reduced by refrigeration and drying to whatever degree is desired. Such gas will protect steel in most processes from oxidation, or scaling, but with this action the difficulties with decarburization increase. The fact that the purpose of these gases is to eliminate the oxidation of iron is the first cause of decarburization, because whatever removal of carbon occurs is not offset, as it is in the open furnace, by the removal of decarburized surface through scaling. Therefore, in bright-heating it is necessary to establish conditions which are neutral to the carbon, if decarburization is to be prevented. In this connection, it is important to differentiate clearly between short- and long-cycle treatments. The requirements of protective gas are entirely different in the two cases, and this point must be kept in mind to avoid confusion and erroneous conclusions regarding the respective merits of the various protective gases.

A summary of data on the principal types of protective gas in common use is given in Table 8, from which a general idea of the different types and their purposes may be obtained, and which will be of assistance in the following discussion.

The gases involved in these atmospheres are the same as in the open furnace, and the causes of trouble are usually wet hydrogen, carbon dioxide, and oxygen. The first is affected by the dewpoint of the gas or other water, the second by the air-gas ratio to the generator, and the third by the tightness of the container in which the protected steel is heated. Such is a condensed statement of the problem, but there are many ramifications to confuse the issue.

The difficulties from wet hydrogen arise from the fact that, according to most authorities, the amount of water vapor needed to cause a decarburizing combination is only 0.1 per cent of the water vapor-hydrogen mixture. This means that rigid control of moisture is essential if reaction with steels containing more than 0.30 carbon is to be controlled. The first step is to dry the gas to a high degree of dryness, as measured by the dewpoint temperature. Table 9 shows the ratio $H_2O/H_2$ for different dewpoint temperatures with a generator gas containing 10 per cent of hydrogen.

Most generators are designed to supply a gas at dewpoint of − 40 deg F or C, and in some cases, notably the annealing of stainless steels, it has been found necessary to go as low as − 70 deg C. The long-cycle annealing of high-carbon steel involves the use of the lean gas generator, where almost

Table 9. Relation between Dewpoint and Water-Hydrogen Ratio for 10% $H_2$ Gas

| Dewpoint temperature (deg C) | (deg F) | Grains water per cu ft of gas | $\frac{H_2O \times 100}{H_2}$ (%) |
|---|---|---|---|
| + 10 | + 50 | 4.80 | 14.3 |
| 0 | + 32 | 2.10 | 6.3 |
| − 10 | + 14 | 0.98 | 2.9 |
| − 20 | + 4 | 0.38 | 1.1 |
| − 30 | − 22 | 0.14 | 0.4 |
| − 40 | − 40 | 0.046 | 0.14 |
| − 50 | − 58 | 0.014 | 0.04 |
| − 60 | − 76 | 0.0036 | 0.01 |
| − 70 | − 92 | 0.0010 | 0.003 |

the theoretical amount of combustion air is supplied to a water-cooled generator, to produce a gas high in $CO_2$ and with only 2 to 8 per cent of combined $H_2$ and CO. The amount of moisture is increased and the capacity of the driers must be greatly increased with this arrangement.

$CO_2$ is the next cause of decarburization to be considered. With the usual 6 : 1 ratio of air to natural gas (or equivalent percentage of air for other hydrocarbon gases) this amounts to about 5 per cent of the gas by volume. For short-cycle hardening or other similar operations (under 30 minutes) or for annealing of low-carbon steels (under 0.30 carbon) this amount of $CO_2$ is not serious. For the treating of higher-carbon steels, however, the $CO_2$ content must be removed. One method utilizes a chemical which will mechanically absorb gaseous $CO_2$ when cold and will give it up when boiled. By using this property in a circulating system comprising an absorbing tower, boiler, and heat-recovery units, it is possible to reduce the $CO_2$ content of the gas to less than 0.3 per cent at a nominal cost. The same method is used in removing the larger quantities of $CO_2$ formed in lean gas generators already mentioned and shown in Table 9.

Having controlled the water vapor, hydrogen, and $CO_2$ entering the furnace or retort, it remains to avoid all oxygen which will combine with the hydrogen to form water vapor and with the CO to form $CO_2$. This oxygen may be in scale on the steel (iron oxide), soaps, lubricants, rust, etc., all of which must be watched carefully in the case of high-carbon steels. The prevention of free oxygen in the furnace or retort is a mechanical problem of sealing, which is solved by properly designed sand seals, water or oil seals outside the furnace, or by other devices.

Problems also arise in connection with the practical application of the gas. One is the obvious necessity for expelling all air from the furnace or retort before the steel reaches a temperature where decarburization may occur, which can best be accomplished by flushing with large quantities of gas at the beginning of the heat. Another is the necessity for drying all condensed moisture from the steel before charging.

The best control of gas flow to the retort is accomplished by measurement

of the dewpoint of the gas at the outlet of the retort. By supplying a relatively large volume of gas at the first part of the cycle, the air in the retort may be purged more quickly, as indicated by a more rapid reduction in the moisture in the outlet gas, which moisture results from the combination of hydrogen in the protective gas with oxygen in the air inside the retort when it is first sealed. A good plan is to supply gas to the retort for about one hour before starting to apply heat. The amount of initial gas flow should be regulated so that for a given retort volume, the dewpoint

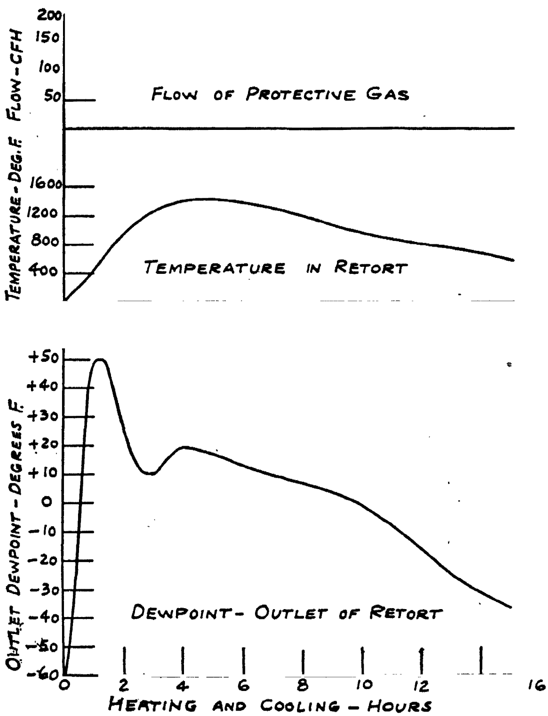


Figure 7. Typical dewpoint of generator gas from retort for "lean mono gas."

will drop to at least as low as plus 10 deg F before the temperature inside the retort reaches a decarburizing temperature of about 1200 deg F. Figure 7 shows a typical variation of dewpoint temperature with an initial gas rate of 200 cu ft per hour through a retort volume of 44 cu ft, in which 800 lbs of steel is contained. The retort in this case is sand-sealed, and the temperatures prevailing through the heating and cooling cycles are shown on the diagram. The dewpoint values are for the protective gas leaving the outlet of the retort, and the gas used is the lean gas, fully conditioned (type 4 of Table 8).

The usual sand seal from 4 to 6 inches deep will hold a pressure of about 3 inches of water in the retort without visible agitation of the sand, or a sufficient agitation to form permanent blowholes in it. The supply of gas should be at regulated pressure not exceeding 3 inches of water, and the quantity of gas should be controlled by a valve in the outlet pipe from the retort, so that line pressure will be available to supply gas at maximum rate when sudden shrinkage of the gas in the retort occurs from rapid cooling of the retort.

As previously described, the inert gas containing hydrogen will contain moisture at the outlet during the initial period of purging because of the combination of hydrogen with oxygen trapped in the retort. The dewpoint temperature will therefore be high at the start and will drop gradually as oxygen is eliminated. After this dewpoint temperature has dropped to 10 deg F or less, the supply of gas to the retort can be reduced to the minimum which will insure pressure in all parts of the retort. With sand seals this is best accomplished by closing the outlet entirely, so that only that gas flows which can leak through the sand seals. With liquid seals a common practice is to have a side outlet pipe from the retort. This outlet is provided with an orifice of the proper size to give the desired minimum flow, and the operator simply closes the outlet beyond the side connection to obtain a fixed minimum flow without valve adjustment. Floscope meters should be provided to measure the flow of protective gas to any installation where consistent results are desired.

A recent development in atmosphere heating is the use of lithium vapor, added to the rich hydrocarbon gas already described. The theory upon which this method is based is that neither $H_2$ nor $CO_2$ will react with the carbon in steel if they are absolutely dry, and that lithium vapor will remove all water vapor or oxygen present in any form in the gas or in the furnace. The vapor reacts with the water to form lithium oxide and free hydrogen. This lithium oxide then reacts with CO to form $CO_2$ and releases the lithium to react again with more water vapor and oxygen. The presence of CO is therefore necessary to insure an efficient operation with minimum lithium consumption. It is claimed that 2 ounces of metallic lithium will condition 2400 cu ft of gas resulting from partial combustion of hydrocarbon gas with 60 per cent of the theoretical air supplied.

This partially burned gas is cooled to room temperature and then passed over metallic lithium heated to vaporizing temperature (about 900 deg F). The resulting mixture is then fed to the furnace in the same way as all other protective gases are used.

In principle, the lithium vapor takes the place of the mechanical driers in other rich gas generator units and, in addition, removes all moisture and oxygen in the furnace and charge. Reports indicate that excellent results have been obtained in the prevention of decarburization in bright-

hardening and short-cycle treatments. Theoretically, it would seem that the method could be extended to long-cycle treatments without $CO_2$ scrubbers, but practical data are not available on this application.

It is probable that continued research with all these protective gases will develop methods for restoring carbon to the surface of steel which has been previously heated in open furnaces, in addition to the methods already developed for preventing further decarburization while heat treating, and that the same furnace equipment will be utilized. Claims have already been made (so-called "skin recovery") in this direction, involving the accurate maintenance of a carburizing atmosphere in perfect balance with the analysis of the steel to be treated.

**Generators**

As has already been stated, two common sources of protective gas at the present time are dissociated ammonia and cracked hydrocarbon gases, the latter being used wherever possible because of the lower cost.

Dissociated ammonia is produced by simple application of heat to pure ammonia from bottles or from storage tanks, depending upon the amount involved. The resulting gas is thoroughly dried, usually in absorption driers which are arranged in duplicate so that one may be reactivated by heat after about 8 hours of operation, while the other dries the gas. One pound of ammonia will produce 45.2 cu ft of dissociated ammonia gas, so that 22 lbs of ammonia are required to produce 1000 cu ft of gas. With an ammonia cost of $0.17 per lb, the cost of the gas is $3.80 per 1000 cu ft. For retort annealing in a tightly sealed retort 54 inches in diameter and 84 inches high, the consumption of ammonia gas can be kept down to about 300 cu ft per ton of steel annealed with a 24-hour cycle by purging the retort with cheap fuel gas before purging for 15 minutes with ammonia. The ammonia is then maintained at a rate of about 25 cu ft per hour until the beginning of the cooling cycle, when the outlet is closed, with ammonia pressure maintained on the retort to replace the shrinkage resulting from cooling. It is claimed that the ammonia consumption can be further reduced by recirculating the gas through several retorts, but a considerable complication is involved in this method. Because of the cost of ammonia gas it is necessary to employ retorts equipped with liquid seals to reduce the consumption to the figures just given.

In hydrocarbon gas generators, such as that of Figure 8, the fuel gas is burned in a brick-lined generator at a temperature of about 2000 deg F in the presence of any one of the several forms of nickel catalyst and with a deficiency of combustion air. The resulting gas is dried to the degree required by the process, and for the control of decarburization in long-cycle annealing of steels containing more than 0.30 carbon the $CO_2$ is removed. This is accomplished, as already stated, by monoethanolamine

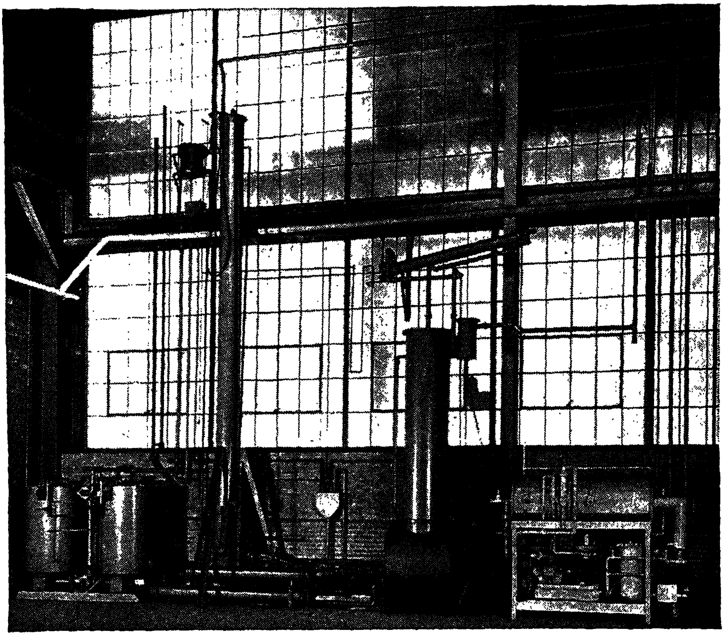

Figure 8. Typical generator for completely conditioned hydrocarbon protective gas.

in liquid form and used in a circulating unit comprising tower and electric boiler. The analysis of rich hydrocarbon gas and lean hydrocarbon gas, before removal of $CO_2$, and obtained from Pittsburgh natural gas with different ratios of air to gas, is as follows:

| Ratio | 6:1 | 7:1 | 8:1 | 9:1 |
|---|---|---|---|---|
| $CO_2$ | 5.5 | 7.0 | 9.0 | 10.5 |
| $CO$ | 9.0 | 7.0 | 5.0 | 2.5 |
| $H_2$ | 15.0 | 11.0 | 7.0 | 3.5 |
| $CH_4$ | 0.8 | 0.5 | 0.1 | 0.0 |
| $O_2$ | 0.0 | 0.0 | 0.0 | 0.0 |
| $N_2$ | 69.7 | 74.5 | 78.9 | 83.5 |

gas after removal of the $CO_2$ will analyze approxin

follows:

| | | | | |
|---|---|---|---|---|
| $CO_2$ | 0.3 max | 0.3 max | 0.3 max | 0.3 max |
| $CO$ | 9.5 | 7.5 | 5.5 | 2.8 |
| $H_2$ | 15.8 | 11.8 | 7.7 | 3.9 |
| $CH_4$ | 0.8 | 0.5 | 0.1 | 0.0 |
| $O_2$ | 0.0 | 0.0 | 0.0 | 0.0 |
| $N_2$ | 73.6 | 79.9 | 86.4 | 93.0 |

With natural gas at $0.40 per 1000 cu ft and a ratio to the generator of 6 parts of air to one part of gas, the consumption of natural gas per 1000 cu ft of protective gas is approximately 143 cu ft and the cost of the protective

gas is \$.057 per 1000 cu ft. The same figure for the lean gas (9 : 1 ratio) is about \$0.04 per 1000 cu ft. To this cost must be added the maintenance and other costs of the generator, which raise the total cost, including all charges, to from \$0.30 to \$0.45 per 1000 cu ft, depending upon the amount of gas made. These costs include natural gas, labor, maintenance, water, power, and charges on the investment, for the lean hydrocarbon gas with $CO_2$ removed and dried to − 60 deg F.

It is evident that this gas is sufficiently cheap that it can be used in much larger quantities than is possible with the much more expensive ammonia gas. The result of this fact is that less complicated sand-sealed retorts may be used with it because leakage is of little consequence.

Charcoal gas is made in a simple generator by passing air over hot carbon in the form of charcoal. The generator must be cleaned and recharged at regular intervals of about 8 hours, and the operation is similar to that of a small gas producer. The analysis of the gas depends upon the temperature maintained in the generator. Ammonia and benzol additions are sometimes made to the charcoal gas, to increase the range of steels which may be treated.

### Some Results with Protective Gases

With this outline of the theory involved, it is interesting to examine the data in Table 10 which shows the decarburization obtained with SAE 1035 and 1060 steels with various protective atmospheres. All these results were obtained in an alloy retort with sand seals which was heated in a direct-fired furnace. The purpose of the treatment was to normalize coiled rods; after heating, the rods were taken from the retort and cooled in air. Tests were made to show that this air cooling had little or no effect on the decarburization, so that all the decarburization occurred in the retort while the steel was surrounded by the gases specified in the tabulation. Where generator gas is specified it was made in all cases from natural gas with an air-gas ratio of 6 : 1 and supplied at a rate between 200 and 300 cu ft per hour to an alloy retort of about 100 cu ft volume in which an average of 4500 lbs of steel was charged. The water vapor and $CO_2$ were removed to various degrees as shown by the analysis of the protective gas in each case.

Table 11 gives typical average results from a number of different steels, all heated in a sand-sealed alloy retort while surrounded by an atmosphere made from partially burned natural gas, from which the moisture had been removed to an extent indicated by a dewpoint of − 60 deg F and from which the $CO_2$ had been removed by means of a monoethanolamine absorption tower. The volume of the retort used was 44 cubic feet, and the flow of gas was about 200 cubic feet per hour in all of the tests. The tabulation includes the maximum dewpoint measured at the retort outlet, which

Table 10. Decarburization in Retort with Protective Atmosphere — Normalizing

| Grade steel SAE | 1035 | 1035 | 1035 | 1035 | 1035 | 1035 | 1035 | 1035 | 1035 | 1060 | 1060 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Atmosphere | air only | natural gas for 8 hr | natural gas for 5 hr | generator gas with 6 : 1 ratio | generator gas 6 : 1 ratio, partly conditioned | generator gas 6 : 1 ratio, partly conditioned | generator gas 6 : 1 ratio, partly conditioned | generator gas 6 : 1 completely conditioned | conditioned generator gas plus natural gas | generator gas conditioned | generator gas conditioned, plus natural gas |
| Temperature (deg F) | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 | 1750 |
| Time in retort (hrs) | 8 | 8 | 8 | 8 | 5 | 5 | 5 | 5 | 5 | 6 | 6 |
| Protective gas analysis | | | | | | | | | | | |
| $CO_2$ | — | — | — | 5.0 | 2.0 | 0.0 | 0.3 | 0.4 | — | 0.1 | — |
| CO | — | — | — | 9.8 | 10.0 | 10.0 | 12.0 | 10.5 | — | 13.2 | — |
| $O_2$ | 21.0 | — | — | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | — | 0.5 | — |
| $H_2$ | — | — | — | 12.1 | 11.6 | 10.8 | 13.0 | 11.9 | — | 12.5 | — |
| $CH_4$ | — | 85.0 | 85.0 | 1.1 | 1.3 | 0.0 | 1.5 | 0.8 | — | 0.8 | — |
| $N_2$ | 79.0 | — | — | 71.9 | 75.1 | 79.2 | 73.2 | 75.4 | — | 72.9 | — |
| Dewpoint (deg F) entering | — | — | — | + 40 | + 25 | + 25 | − 22 | − 30 | − 40 | − 40 | − 40 |
| Rod surface | mill scale | mill scale | mill scale | mill scale | mill scale | mill scale | mill scale | pickled | pickled | bright | bright |
| Decarburization (in) (microscope) | | | | | | | | | | | |
| Complete | — | 0.025 | — | 0.020 | 0.010 | 0.010 | 0.005 | — | — | — | — |
| Partial | 0.020 | recarburized | 0.010 | 0.030 | 0.016 | 0.015 | 0.010 | 0.015 | 0.010 | 0.012 | 0.005 |
| Total depth | 0.020 | — | 0.010 | 0.050 | 0.026 | 0.025 | 0.015 | 0.015 | 0.010 | 0.012 | 0.005 |

occurred during the first part of the heating cycle as the result of the combination of residual air, leakage air, or oxygen from impurities of the steel with hydrogen of the protective gas. The ultimate dewpoint of the gas at the end of the cooling cycle and also taken at the outlet of the retort is included, which affords an idea of the tightness of the retorts. Analysis of the generator gas is given where available, as well as the ratio of air to gas entering the generator; $CO_2$ was removed from the gas in all cases.

The test for decarburization or recarburization in all these tests was by analysis of three samples of wire or rod before annealing, compared with adjacent samples from the same coils after annealing. The chemical analysis for carbon was made from turnings of 0.010 inch from the diameter of the pieces, with no discard.

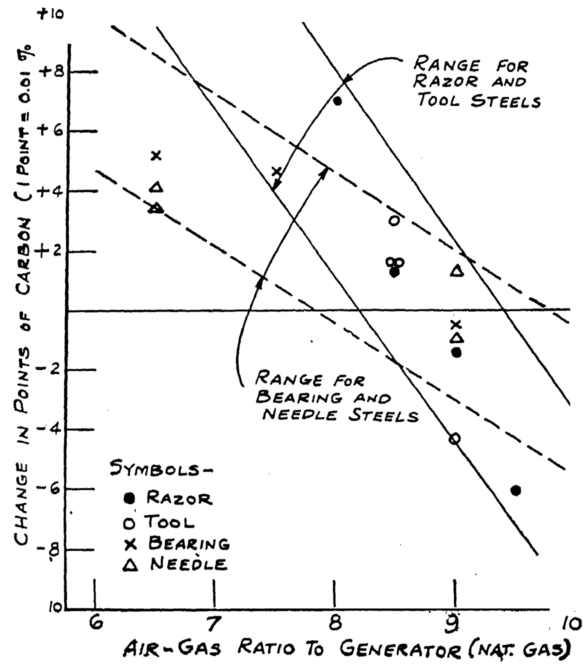


Figure 9. Carbon change in long cycle annealing with hydrocarbon protective atmosphere (IV in Table 8).

Figure 9 shows graphically the relation between recarburization (above the zero line) or decarburization (below the zero line) and the air-gas ratio to the generator, for the same steels as in Table 11. It was prepared from a large number of tests in each case, all made in a manner identical with the typical tests of Table 11. For each steel, the range of results obtained in practical operation is shown.

A study of Table 11 and Figure 9 will disclose much interesting information concerning the actual production results from heating these steels in

protective atmospheres made from natural gas with various air-gas ratios (fully conditioned lean gas, No. 4 in Table 8). The results are practical, in that they include the variations arising from leaks in the retorts, fluctuations in generator operation, variations in natural gas, drawing compounds or slight rust on the wire, and variations in the chemical analysis of the steel. The information answers to some extent the common question of the ratio variation required in the treatment of different steels to avoid changes in the surface carbon content. The practical answer is that for retort annealing the lean ratio gas is neutral within necessary limits to most steel analyses. For very sensitive steels, such as those containing a considerable percentage of molybdenum, further adjustment is possible by regulation of the quantity of gas passing through the retort.

This concludes the discussion of the subject of decarburization. It is hoped that further information may be accumulated, to the point where a better understanding of the phenomena may be developed. It constitutes a major problem in the steel industry, and is making slow progress, because almost all available data are incomplete. From the outline presented it is evident that many factors affect the reaction, and unless evidence pertaining to all these factors is included, a report of decarburization may be misleading and without value.

Many of the different types of furnaces involved in making use of these protective gases are described in Chapter 7. A summary of the various furnaces now being used with protective gas atmospheres would include the following principal groups:

**Batch Type Furnaces**

(1) Relatively small, box-type furnaces without muffles, heated by electricity or by radiant tubes, with sealed outside shell to contain protective gas. Material charged on alloy hearth, roller rails, or small car. Used for hardening and annealing of a variety of small pieces.

(2) Muffle or retort furnaces of box type, car type, or removable-hood type, heated either by direct firing outside the retorts or by electricity or radiant tubes. Used for hardening small pieces and for all kinds of annealing (both short and long cycle) of bars, wire coils, strip coils, and sheets (Figures 202, 216, 217, 218, 219).

**Continuous Furnaces**

(1) Sealed-shell furnaces without muffles or retorts, heated by electricity or by radiant tubes and utilizing rollers, roller rails, chains, chain belts, woven wire belts, shaker hearths, etc. for conveying. Used for brazing and hardening small pieces and for intermediate annealing of bars, tubes, coils of wire or strip, and sheets (Figures 114, 118, 126, 208, and 220).

(2) Muffle furnaces, heated by direct-fired fuel or by electricity, with conveying by chains, roller rails, shaker hearths, etc. Used for strand-annealing of wire and strip (usually pulled through tubular muffles) and for special gas applications for other products.

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# Chapter 2

## Fuels and Burner Equipment

The first consideration in the study of this subject is the quantity of fuel required to maintain the desired temperature in a furnace under the conditions for which it is designed. The determination of fuel requirements is an extensive subject which has been discussed in detail by W. Trinks* and the author.† It is not the purpose of this book to repeat this discussion. For the sake of completeness, however, it is desirable to include a tabulated summary of data used for this purpose. Also, there is a real need for more rapid methods of estimating fuel requirements, which is a subject of special interest to the author, and which will be discussed in further detail in this chapter.

The individual calculation of fuel requirements involves a separate mathematical determination of each of the heat requirements, which include any or all of the following: chemical and sensible heat in the fuel (see combustion tables), heat absorbed by the steel, heat to conveyors or carriers, sensible heat in the flue gases, radiation and heat absorbed by the furnace refractories, and radiation through furnace openings. Table 12 has been prepared to show in condensed form the numerical values for various furnace temperatures of those factors which vary with temperature. The use of this information can be found in the texts already mentioned, but a good idea of the method may be gained from a simple example.

As such an example, consider a furnace with inside dimensions 20 ft long × 4 ft wide × 4 ft high, through which a total weight of 2000 lbs of steel parts and conveying trays are pushed per hour, and heated to a temperature of 1600 deg F. The furnace lining consists of 9 in of firebrick with 5 in of insulation. The fuel is natural gas with a net heating value of 1000 Btu per cubic foot. The simple calculation of heat requirements, using the values of Table 12, will be:

| | |
|---|---|
| Heat to steel and trays 2000 lb × 245 | 490,000 Btu per hr |
| Heat to furnace walls 352 sq ft × 339 × 2.0 (Table 14) | 238,700 |
| Radiation through door openings 6 in high both ends 576 sq in × 210 | 122,000 |
| | 850,700 Btu per hr |

* Trink, W, "Industrial Furnaces," John Wiley and Sons, New York.

† "Practical Industrial Furnace Design," John Wiley and Sons, New York, 1928.

Table 12. Data for Calculation of Fuel Requirements

| Firebrick (in) | Insulation (in) | Furnace temperature (deg F) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 | 2200 | 2400 |
| | | Heat absorbed by steel (Btu per lb) | | | | | | | |
| | | 100 | 120 | 142 | 245 | 290 | 320 | 350 | 380 |
| | | Sensible heat in flue gases (% heat in fuel) (Average for various fuels — See Combustion Table 21) | | | | | | | |
| | | 23 | 28 | 33 | 38 | 44 | 49 | 55 | 60 |
| | | Radiation from furnace walls (Btu per sq ft per hr) (Values for "steady state" conditions) | | | | | | | |
| $4\frac{1}{2}$ | 0* | 1050 | 1250 | 1480 | 1860 | 2130 | — | — | — |
| $4\frac{1}{2}$ | 5 | 216 | 300 | 375 | 450 | 530 | 610 | — | — |
| 9 | 0 | 550 | 700 | 860 | 1040 | 1220 | 1400 | 1600 | 1790 |
| 9 | 5 | 204 | 244 | 269 | 339 | 364 | 429 | 490 | 550 |
| $13\frac{1}{2}$ | 0 | 405 | 500 | 590 | 700 | 830 | 975 | 1120 | 1270 |
| $13\frac{1}{2}$ | 5 | 166 | 204 | 244 | 259 | 314 | 349 | 396 | 450 |
| 18 | 0 | 264 | 365 | 460 | 560 | 660 | 760 | 865 | 960 |
| 18 | 5 | 149 | 181 | 215 | 247 | 280 | 311 | 349 | 390 |
| | | Radiation through large openings (Btu per sq in per hr) | | | | | | | |
| | | 50 | 90 | 145 | 210 | 300 | 425 | 560 | 740 |

* Where light refractories are used, the conductivity of this material is approximately one-half that of firebrick. Therefore, the loss will be about the same as that from twice the thickness of firebrick. For example, the loss from a wall of 9 in of light refractory will be about equivalent to that from 18 in of firebrick in the above table.

For each cubic foot of natural gas burned, 1000 Btu enters the furnace, of which, from Table 12, 38 per cent or 380 Btu leaves the furnace as sensible heat in the flue gases. The net heat available in the furnace is therefore 620 Btu per cubic foot of gas burned.

The gas required per hour is $\frac{850{,}700 \text{ Btu per hour}}{620 \text{ Btu per cu ft}}$ which is 1370 cu ft of natural gas per hour.

In the calculation of heat to the furnace walls in the example, a factor of 2.0 was used as a multiplier to increase the value for radiation from Table 12, which gives the practical figure for radiation with steady state conditions when the walls have been thoroughly soaked after a long period of heating. In actual practice the walls of the furnace seldom reach this condition, and the factor is used to include the heat absorbed by the furnace walls. The factor is taken from the simultaneous method of calculating absorption and radiation which was presented in the author's previous book. Since that time further data have been developed which improve the approximations necessary when these factors were first developed. It is of interest to discuss this subject further at this point.

**Simultaneous Determination of Absorption and Radiation**

After the interior of a furnace has been brought to operating temperature, the heat requirements per square foot commence to vary with the wall

construction. This variation gradually increases until the furnace lining has become thoroughly saturated and the "steady state" or equilibrium condition has been reached. After this, the true radiation for this condition depends entirely upon the thickness of firebrick and insulation.

This discussion is based on data obtained from a large number of experimental tests in a test furnace and in commercial installations. The procedure in all cases was to determine the temperature at various points through the thickness of different wall, arch, and hearth constructions at fixed intervals of time throughout the cycle of operation. From these

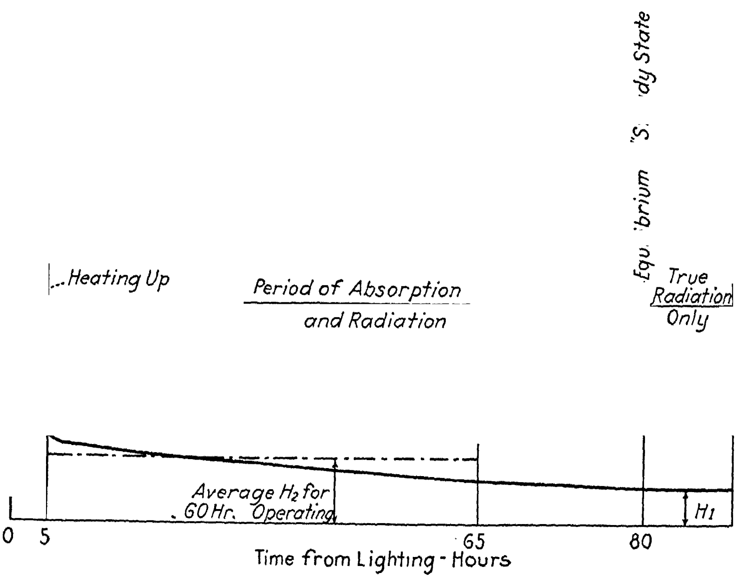



Figure 10. Variation of heat absorption with time for an average furnace wall.

values of temperature, the heat absorbed during each interval was calculated, and the resulting values plotted against elapsed time of operation. This treatment of such experimental data has established comparatively simple relationships, by means of which both heat absorption and radiation during operation may be simultaneously determined by one calculation for a given set of operating conditions. This is in contrast with the usual method of separately calculating absorption and radiation from a series of assumptions concerning the percentage of heat saturation in the lining.

A graphical idea of the heat flow from the time of lighting a furnace is given in Figure 10. In the range of heating from cold to operating temperature the curves for heat absorbed by all wall thicknesses using firebrick and insulation are practically identical. The lining of the furnace is absorb-

ing heat, and radiation from the outside is low when actual operation of the furnace begins. From this point the radiation gradually increases and the absorption decreases until equilibrium is reached, when the lining is saturated and the heat entering the wall is exactly equal to that radiated. The numerical value of this radiation, $H_1$ in Figure 10 for steady state or equilibrium conditions, is well known for different thicknesses of firebrick and insulation. All that is necessary to calculate absorption and radiation in one operation is to determine the average value of $H_2$ in the range of time in which the furnace is operated and for the proper wall construction.

In the course of such determination the effect of the following factors must be considered:

(1) Furnace temperature during operation
(2) Thickness of firebrick and insulation
(3) Rate of heat liberation
(4) Time and cycle of operation

An experimental test furnace was used for the development of a part of the data and a large number of tests on refractory walls were performed. Typical tests are outlined in detail below, and they correspond in actual practice to the case where a cold furnace and charge are to be heated and soaked for a known time, or where the furnace has been heated empty from cold and material is to be heated continuously for a known length of time. The problem is to determine quickly the heat to the refractories for radiation and absorption.

The test furnace used was 6 ft wide × 5 ft deep × 3 ft high, fired from one side. A wall construction of $13\frac{1}{2}$ in of firebrick and $2\frac{1}{2}$ in of insulation was selected for temperature measurements. Figure 11 shows the progressive temperature curves through the wall in Test 4 of Figure 12.

For each of the curves of Figure 11, the average temperatures of firebrick and insulation were found. For example, the average temperature after 2 hours of heating was 350 deg F for the firebrick and 90 deg F for the insulation. After 3 hours these temperatures were 384 deg F and 95 deg F respectively. The heat gained hourly by each square foot of firebrick was

$$157 \text{ lb brick} \times 0.25 \text{ specific heat} \times (384 - 350 \text{ deg F}) = 1330 \text{ Btu}$$

This represents the rate of absorption for the average elapsed time or $2\frac{1}{2}$ hours. Similarly, the heat gained by the insulation is 22 Btu per sq ft hourly in the same period, so that the total hourly absorption is 1352 Btu per sq ft. The radiation from the outside of the wall can be neglected for this calculation, but must be added as the outside temperature increases.

By repeating this calculation for each curve representing a set of temperature readings, the curves of Figure 12 were prepared. These curves show the conditions for four characteristic tests selected as most typical of a group of tests, all of which showed consistent agreement.

Test 4 consisted in heating the direct-fired furnace to 1700 deg F and holding it at that temperature. Test 6 was similar, but with 1300 deg F temperature, and with the furnace bottom altered to form a combustion chamber for underfiring, instead of direct firing from the top of one side wall. Test 13 was heating to 1000 deg F, with the furnace again fired from one side direct and the solid bottom restored. Test 26 is again direct-fired, and the furnace is heated at an unusually high rate of heat liberation to 1600 deg F. All temperatures are the average readings of six thermocouples distributed in the furnace heating chamber.

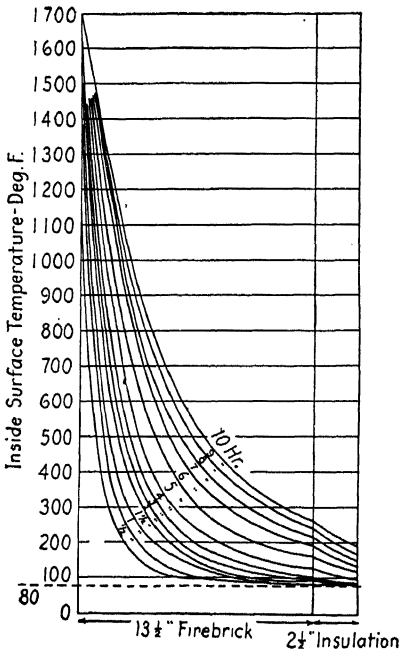



Figure 11. Progressive temperature curves through the wall of a direct-fired furnace heated in 10 hr. to 1700 deg F.

It will be noted from Figure 12 that the curves for the 1700 and the 1300 deg F tests are almost identical in this range. This is explained by the fact that the rate of heat liberation did not vary greatly in these tests. The effect of an exceptionally high rate of heat liberation is shown by the curve of Test 26. In the 1000 deg F test the rate of heat liberation was about one-half that for the two average tests, and the rate of heat absorption was lower in the first few hours.

Let us now consider the practical application of the data of Figure 12 and other similar tests to furnace calculations. The simple method of calculating the heat given to refractories is to start in all cases with the true radiation value corresponding to equilibrium for the particular wall, roof,

or bottom construction under consideration. The practical values for true radiation from various refractory thicknesses are given in Table 13.

Table 13. * True Radiation from Various Walls at Differing Temperatures (Btu)

| Firebrick (in) | Insulation (in) | Furnace temperature (deg F) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1,000 | 1,200 | 1,400 | 1,600 | 1,800 | 2,000 | 2,200 |
| 4½ | 0 | 1,050 | 1,250 | 1,480 | 1,860 | 2,130 | — | — |
| | 2½ | 450 | 510 | 600 | 720 | 850 | 1,005 | — |
| | 5 | 216 | 300 | 375 | 450 | 530 | 610 | — |
| | 7½ | 178 | 215 | 265 | 315 | 362 | 410 | — |
| | 10 | 150 | 185 | 220 | 260 | 295 | 330 | — |
| | 12½ | 140 | 165 | 190 | 220 | 250 | 280 | — |
| 9 | 0 | 550 | 700 | 860 | 1,040 | 1,220 | 1,400 | 1,600 |
| | 2½ | 310 | 380 | 460 | 560 | 660 | 762 | 865 |
| | 5 | 204 | 244 | 269 | 339 | 364 | 429 | 490 |
| | 7½ | 170 | 200 | 232 | 266 | 300 | 334 | 370 |
| | 10 | 140 | 170 | 199 | 226 | 253 | 281 | 310 |
| | 12½ | 125 | 150 | 170 | 190 | 212 | 235 | 260 |
| 13½ | 0 | 405 | 500 | 590 | 700 | 830 | 975 | 1,120 |
| | 2½ | 230 | 300 | 380 | 455 | 535 | 615 | 705 |
| | 5 | 166 | 204 | 244 | 259 | 314 | 349 | 396 |
| | 7½ | 150 | 175 | 200 | 226 | 255 | 285 | 320 |
| | 10 | 128 | 150 | 176 | 200 | 228 | 254 | 280 |
| 18 | 0 | 264 | 365 | 460 | 560 | 660 | 760 | 865 |
| | 2½ | 180 | 239 | 267 | 319 | 367 | 455 | 515 |
| | 5 | 149 | 181 | 215 | 247 | 280 | 311 | 349 |
| | 10 | 127 | 148 | 170 | 194 | 220 | 240 | 270 |

* From "Practical Industrial Furnace Design," Mawhinney, John Wiley & Sons, New York.

We have already stated that the heat absorption in furnace linings is practically independent of the wall construction for the time required to heat up; after this, radiation becomes more important in comparison with absorption, and the values diverge until the refractories are saturated. Then the fixed values of Table 13 pertain to the wall thickness.

Regardless of wall construction and final temperature, and for usual rates of firing, tests indicate that when a furnace lining has reached operating temperature, the rate of heat absorption by the interior is about 1200 Btu per square foot per hour (an elapsed time of 5 to 6 hours on Figure 12) and that from that point the curve approaches a straight line. By taking advantage of these facts and the known values of Table 13 we can calculate the hourly decrease in rate of absorption, if we know the time required to reach equilibrium.

Careful tests to determine this time to reach equilibrium show the following values for three different refractory constructions:

| | |
|---|---|
| 9-in firebrick with no insulation | 30 hrs |
| 9-in firebrick with 5-in insulation | 50 hrs |
| $13\frac{1}{2}$-in firebrick with $2\frac{1}{2}$-in insulation | 60 hrs |

Considering the example of Test 4 in Figure 12 and assuming a time of 60 hours to reach equilibrium for the wall, the hourly rate of absorption

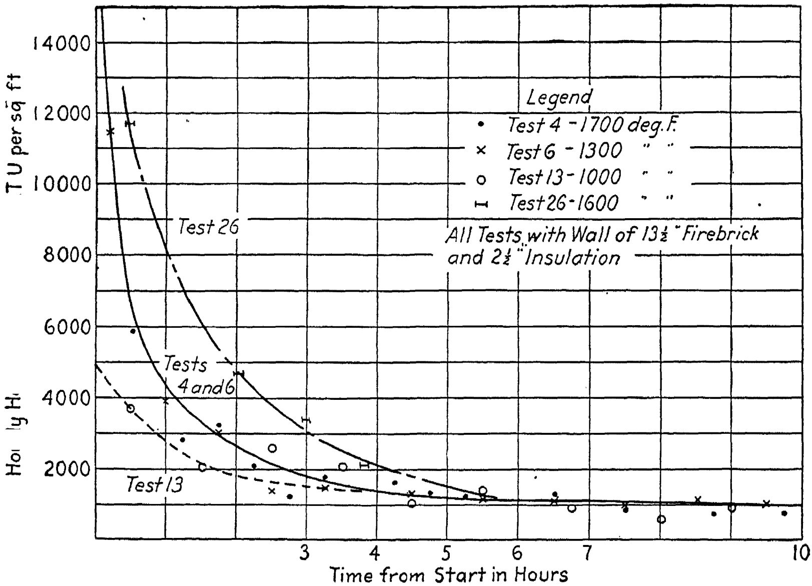



Figure 12. Absorption of furnace refractories under various rates of heating and various final temperatures.

plus radiation when the furnace is ready to operate (6 hours) is 1200 Btu per sq ft per hour, and the true radiation hourly for 1700 deg F at 60 hours is 500 Btu per sq ft, from Table 13. The hourly drop per sq ft is then

$$\frac{1200 - 500}{54 \text{ hrs operating}} \quad 13 \text{ Btu}$$

To find the heat supplied to the refractories per sq ft for an operating interval of 10 hours after the furnace is hot, the value will be

$$1200 - \left(\frac{10 \text{ hrs}}{2} \times 13 \text{ Btu hourly decrease}\right) = 1135 \text{ Btu per sq ft per hr}$$

The factor for multiplication of the proper value from Table 13 is therefore 1135/500, or 2.3. During a period of 40 hours after heating, the average heat hourly to the refractories would be $1200 - \left(\frac{40 \text{ hrs}}{2} \times 13\right)$ or 940 Btu, and the factor would be 940/500, or 1.9.

Table 14 has been prepared to show these factors for different intervals of time after the furnace is hot and for different lining constructions.

Table 14. Factors, Total Heat Supplied, Divided by Radiation at Equilibrium

| Firebrick (in) | Insulation (in) | Operating period, hrs | | | |
|---|---|---|---|---|---|
| | | 10 | 20 | 60 | 100 |
| 4½ | 0 | 1.0 | 1.0 | 1.0 | 1.0 |
| | 10 | 4.3 | 4.0 | 2.6 | 1.4 |
| 9 | 0 | 1.1 | 1.1 | 1.0 | 1.0 |
| | 5 | 3.3 | 3.0 | 2.0 | 1.5 |
| | 10 | 5.1 | 4.8 | 3.8 | 2.8 |
| 13½ | 0 | 1.6 | 1.5 | 1.1 | 1.0 |
| | 5 | 4.4 | 4.0 | 2.9 | 2.2 |
| | 10 | 5.7 | 5.4 | 4.2 | 3.1 |
| 18 | 0 | 2.0 | 1.9 | 1.5 | 1.1 |
| | 5 | 4.6 | 4.4 | 3.6 | 2.8 |

As an example of the use of the above data, take an oil-fired furnace 20 ft long × 6 ft wide × 4 ft high. After being heated to 1500 deg F in 5 hours it is to be operated at that temperature for 20 hours. How much oil will be required for the refractories during operation?

Assume the furnace is constructed as follows:

| | |
|---|---|
| Roof | 9 in firebrick with 5 in insulation |
| Walls | 13½ in firebrick with 5 in insulation |
| Bottom | 18 in firebrick with no insulation |

Then,

| | | | |
|---|---|---|---|
| Roof | 120 sq ft × 304 (Table 13) | × 3.0 (Table 14) | = 110,000 Btu per hr |
| Walls | 208 sq ft × 252 | × 4.0 | = 210,000 |
| Bottom | 120 sq ft × 510 | × 1.9 | = 116,000 |
| | | | 436,000 Btu per hr |

If the gases leave the furnace at 1600 deg F, the proportion of their heat available in the furnace for useful work is 63 per cent. Hence the fuel required is

$$\frac{436{,}000 \text{ Btu}}{0.63 \times 140{,}000 \text{ Btu per gallon}} = 4.95 \text{ gallons of oil per hr}$$

In contrast with the foregoing examples of furnaces which are heated from cold (Monday morning after week-end shut-down, or occasional operation with intervening days), are furnaces which are brought to temperature and held there for comparatively long periods of time. This time may vary from a full week of continuous operation (130 hours), as in continuous mill and heat-treating equipment, to 12 months (8760 hours) or more, as for continuous kilns. The heat flow in such cases may be calculated from data already presented, but it is interesting to see the details of the heat flow for a typical example.

Figure 13 shows the lines of temperature distribution for a wall constructed of $13\frac{1}{2}$ in of firebrick and 5 in of insulation in a continuous carburizing furnace which was slowly dried out after construction. The temperature values were obtained by periodic readings of thermocouples buried in the furnace wall at different depths. The initial rate of heating was quite slow, to drive off the moisture in the fireclay.

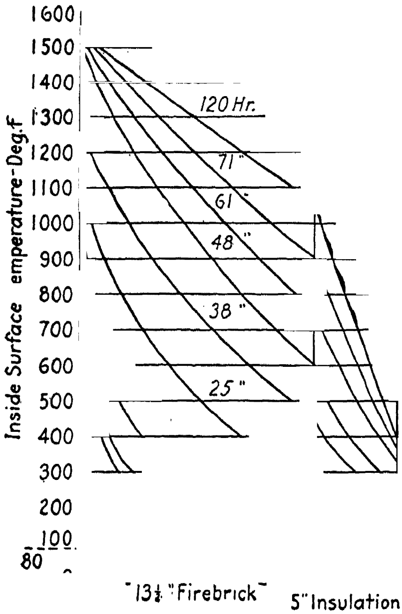



Figure 13. Temperature distribution through the wall of a continuous carburizing furnace which was slowly dried out after construction.

By the method already explained for calculating successive heat contents of the wall with known intervals between curves, the rate of heat absorption was calculated. This is shown in Figure 14 as a function of average time elapsed from lighting. The true curve of Figure 14 represents the actual variation in absorption rate with time, and the effect of the heat required to drive off the water vapor is clearly shown by the drop in the apparent rate of absorption, as measured by brick temperatures, during the first 30 hours or so after lighting.

The probable curve if the brickwork were dry is also shown by the broken line of Figure 14, taking into account the comparatively low rate of heat liberation in the furnace when drying out. In this test no further change in brick temperature was found after 120 hours of very slow heating had elapsed from the time of lighting. After 120 hours the rate of heat flow is in the equilibrium state with no heat absorption. With normal rate of heating of dry refractories, this time would be about 70 hours. From Table 13 the true radiation for a wall of $13\frac{1}{2}$ in firebrick with 5 in of insula-

tion is 286 Btu per square foot hourly, and the agreement of the test figure with this value can be seen from Figure 14.

A third common method of furnace operation is to heat the furnace for only 10 hours a day, but to operate consistently for 5 or 6 days per week. It is obvious that the furnace will not cool off entirely over night, and that therefore the rate of heat absorption will be less in the latter part of the week than it is for the first day. To duplicate this condition, a series of tests was arranged for the test furnace, in which a cycle of 10 hours' heating was followed each day, starting at the same time each morning and operating at the same temperature of 1600 deg F.

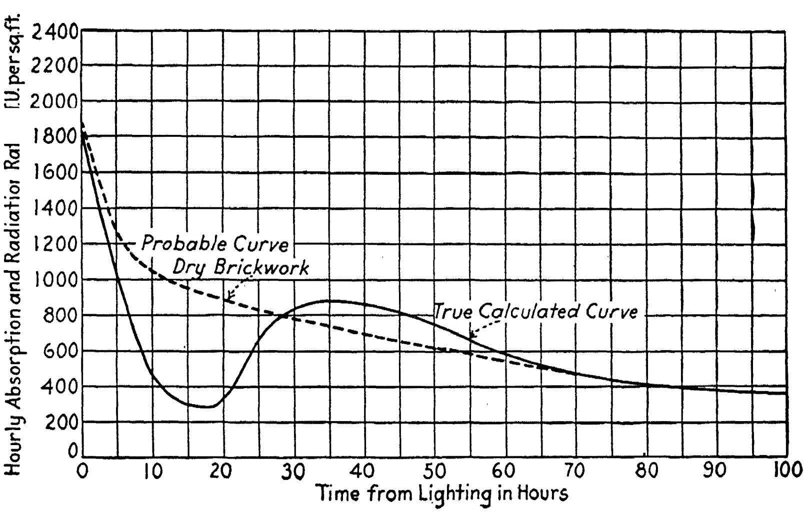



Figure 14. Drying curve for continuous carburizing furnace, showing effect of driving off moisture from the brickwork during the first 30 hours.

In these tests temperatures in the brickwork were periodically observed, and the rate of heat absorption was determined in exactly the same manner as for former tests. Results of these calculations, given in Figure 15, show the variation in rate of absorption with elapsed time. One will observe a considerable decrease in heat absorption the second day as compared with the first day; a progressively lesser decrease the third and fourth days; and practically no change after the fourth day.

Since these measurements were made in a wall consisting of $13\frac{1}{2}$ in of firebrick and $2\frac{1}{2}$ in of insulation, the true radiation constant for equilibrium conditions is 455 Btu per square foot hourly (Table 13).

Factors in Table 15, for comparison with true radiation, have no useful value or connection with Table 14 in this case, because the time used is from the instant of lighting, rather than from the time of reaching temperature. In this case of repeated heating, the absorption rate must include

the heating of the furnace, as it is also a variable; therefore, the absorption will vary with final temperature and with the wall construction, and will not be in constant relation to true radiation.

Table 15. Varying Absorption with Intermittent but Regular Operation

| | Absorption hourly (Btu per sq ft) | Ratio to tru radiation |
|---|---|---|
| Average for first day | 2,660 | 5.8 |
| Average for second day | 2,180 | 4.8 |
| Average for third day | 2,029 | 4.5 |
| Average for fourth day | 1,900 | 4.2 |
| Average for fifth day | 1,900 | 4.2 |
| Average for week | 2,134 | 4.7 |

Summarized from the above discussion, the conclusions may be as follows:

(1) In fuel-fired furnaces constructed of firebrick, the fuel required to heat to operating temperature is practically independent of the usual wall construction; during operation the fuel consumption is affected by the refractory design.

(2) The calculation is more simple, and the information derived is more valuable as a basis for burner and furnace design, if the fuel for heating up and that for operating are calculated separately.

(3) During the operating period, the heat to refractories includes that for both radiation and absorption. The total heat so used hourly decreases as the time increases until equilibrium is reached, when absorption is completed and all heat supplied represents the minimum and constant value for true radiation.

(4) The simple relation between the known values of true radiation for common refractory combinations and the average total of absorption and radiation for various operating periods of time can be determined with practical accuracy, and are given in Table 14. Application of these data to practical calculations of fuel consumed is simple.

(5) When a furnace is operated continuously for long periods the refractory lining reaches equilibrium, and the only loss of heat to refractories is true radiation. In such cases, the heat absorbed by the refractories is of less importance to the fuel economy.

(6) Intermittent operation, consistently repeated each day, lowers the average heat required by the refractories, in comparison with a single heat. The ratio of reduction has been experimentally determined for a wall of $13\frac{1}{2}$ in of firebrick and $2\frac{1}{2}$ in insulation, where the average total of absorption and radiation requirements for a series of six consecutive daily operations of 10 hours each day has been found to be only 80 per cent as great as the same requirement for the first day, which represents a single turn, starting with a cold furnace.

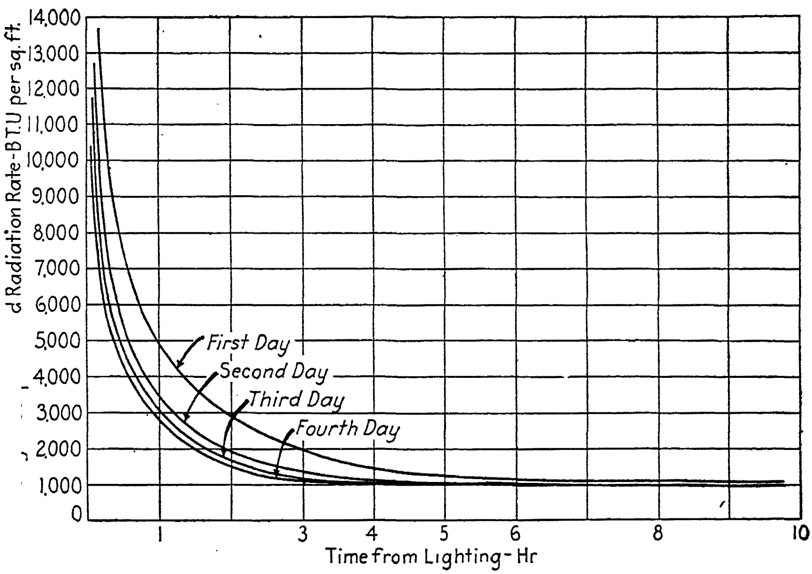



Figure 15. Furnace used day after day, and allowed to cool during the night, requires less heat successively for several days; as the period increases, the heat requirement becomes uniform.

## Rapid Estimation of Fuel Requirements

An equally interesting investigation by the author which is pertinent at this point is the question of the heating of refractories from cold to operating temperature. A relation established between the heat liberated per sq ft of furnace refractories and the time required for the empty furnace to reach operating temperature can be used as a rapid and effective method of estimating the fuel requirements of a furnace, as will be explained.

Before proceeding with the details of this investigation, it is desirable to outline the factors which affect the heat absorption under heating-up conditions. These are:

(1) The heat storage which exists in the refractories when the furnace is considered "up to temperature" and ready for operation.
(2) The effect of the final operating temperature on the time and fuel required to heat up (empty furnace).
(3) The effect of the wall thickness and amount of insulation on the time and fuel required to heat up (empty furnace).
(4) The effect of variation in the rate of heat liberation, as compared with a steady rate of heat liberation throughout the heating-up period.

The test furnace used was the same as already described for the previous investigation, and was direct-fired in this case. Into this furnace, at different times, gas was fired at rates of 500, 750, and 1000 cu ft per hour, the

gas being natural gas with a net heating value of 1050 Btu per cubic foot. With these rates of firing the time required to bring the average of the six thermocouples to several different temperatures was determined, as shown in Table 16 below and by the dotted lines of Figure 16. Some idea of the magnitude of these selected firing rates is afforded by the fact that after ten hours at temperature, this test furnace requires 360 cubic feet of gas per hour to hold it at 1500 deg F and 250 cubic feet of gas per hour to hold it at 1000 deg F.

Table 16. Time Required to Heat Up Test Furnace

| Final temperature (deg F) | Gas/hr (cu ft) | Heat liberated (Btu/sq ft hourly) | Time to r operati temperatu |
|---|---|---|---|
| 1,000 | 500 | 3,900 | 4.5 |
| | 750 | 5,830 | 1.8 |
| | 1,000 | 7,800 | 1.1 |
| 1,200 | 500 | 3,900 | 8.5 |
| | 750 | 5,830 | 2.8 |
| | 1,000 | 7,800 | 1.9 |
| 1,400 | 500 | 3,900 | 15.0 |
| | 750 | 5,830 | 4.8 |
| | 1,000 | 7,800 | 2.5 |
| 1,600 | 500 | 3,900 | 23.0 |
| | 750 | 5,830 | 7.7 |
| | 1,000 | 7,800 | 3.2 |

These tests are for constant rate of heat liberation per sq ft of furnace interior over the entire period of heating up (dotted lines in Figure 16), whereas in actual practice the rate of firing is usually high at the start and gradually less as the furnace heats up. Most furnaces are equipped with automatic temperature control which operates in the same manner, because, when the furnace gases reach the desired temperature, the control reduces the fuel rate while the refractories approach this temperature.

The method of using high heat input at the start is quicker and more efficient in attaining heat storage adjacent to the inside surface of the refractory lining, and is more representative of actual practice. To determine the difference between the two methods of operation and a curve of more practical value, a large number of tests was performed in the test furnace. Of 14 such tests, in all of which the furnace was heated rapidly, four examples have been selected for detailed outline of data, as indicated in Table 17.

From the sample tests in this tabulation and from the other tests with varying conditions, the heavy lines in Figure 16 were drawn for the 1000 and 1500 deg F temperatures. As no tests in the experimental furnace were carried above 1650 deg F, the line for the 2000 deg F temperature was determined from the commercial furnace tests described below.

From a study of the corresponding dotted and solid lines of Figure 16 it is evident that a furnace may be brought up to temperature more quickly by firing hard at the start and reducing the fuel input as the furnace lining approaches the desired temperature than is possible by firing at a constant rate equal in value to the average of the variable rate.

Table 17. Rate of Heat Liberation

| Time (hrs) | Btu per sq ft of furnace interior per hr Test No. 13 | Test No. 14 | Test No. 21 | Test No. 23 |
|---|---|---|---|---|
| ½ | 3,120 | 8,400 | 5,200 | 1,070 |
| 1 | 2,600 | 10,200 | 5,200 | 6,700 |
| 1½ | 2,910 | 6,750 | 5,200 | 4,440 |
| 2 | 2,760 | 7,000 | 4,900 | 5,500 |
| 2½ | 2,760 | 7,150 | 5,650 | 5,950 |
| 3 | 2,910 | 7,150 | 4,730 | 6,250 |
| 3½ | 2,910 | 6,700 | 6,250 | 5,950 |
| 4 | 2,580 | 5,800 | 5,650 | 5,200 |
| 4½ | 2,410 | 5,800 | 5,500 | 5,350 |
| 5 | 2,250 | 5,050 | 5,650 | 5,020 |
| 5½ | 2,250 | 5,030 | 5,500 | 5,800 |
| 6 | —— | 5,030 | —— | —— |
| Average heat liberation | 2,678 | 6,672 | 5,635 | 5,203 |
| Final temperature (deg F) | 900 | 1,600 | 1,600 | 1,550 |
| Time (hrs) | 5½ | 6 | 5½ | 5½ |
| Average gas hourly (cu ft) | 350 | 875 | 740 | 680 |
| Cu ft of gas, hourly to hold at temperature. | 250 | 440 | 440 | 400 |

In commercial furnace tests identically the same procedure was followed as in the experimental furnace tests with variable heat input. During the routine heating of various empty furnaces from cold, the time and fuel consumption were determined when the furnace was apparently hot throughout, which was usually from 1 to 2 hours after the control thermocouple had reached the desired temperature. A summary of the data is given in Table 18. It is noticeable that those practical commercial results which involve furnaces heated to 1500 deg F check very closely with the curves derived from the experimental furnace.

As an example of the use of the curves of Figure 16, suppose that a batch furnace, underfired with natural gas, is 5 ft wide, 20 ft long, and 2 ft high from hearth to arch skew line, and is used for heating rods at 1800 deg F. The furnace is to be heated empty from cold to operating temperature; the question is, How long will it take?

Suppose that the maximum burner capacity available is 10,000 cu ft of natural gas per hour and that the inside area of the furnace, includ-

Table 18. Tests in Commercial Furnaces

| Furnace type | Operating temperature (deg F) | Fuel | Interior area (sq ft) | Average heat liberated per sq ft (Btu hourly) | Time to heat (hrs) | Walls: Fire-brick (in) | Walls: Insulation (in) |
|---|---|---|---|---|---|---|---|
| Car-type annealing | 1,350 | Nat. gas | 1,200 | 8,300 | 2 | 9 | 5 |
| Batch rolling mill | 1,900 | Oil | 312 | 14,800 | 4 | 18 | $2\frac{1}{2}$ |
| Chain-hearth heat treating | 1,500 | Nat. gas | 228 | 3,500 | 11 | 7 | 10 |
| Tunnel kiln | 1,500 | City gas | 540 | 2,040 | 23 | $13\frac{1}{2}$ | $7\frac{1}{2}$ |
| Rotary hearth | 1,900 | Nat. gas | 1,760 | 5,550 | 8 | $13\frac{1}{2}$ | $2\frac{1}{2}$ |
| Batch forging | 2,300 | Oil | 318 | 8,100 | 7 | $22\frac{1}{2}$ | $2\frac{1}{2}$ |
| Continuous pusher carburizing | 1,600 | Nat. gas | 305 | 5,900 | $5\frac{1}{2}$ | 9 | 10 |
| Continuous pusher forging | 2,300 | Nat. gas | 295 | 23,700 | $4\frac{1}{2}$ | $13\frac{1}{2}$ | $2\frac{1}{2}$ |
| Pusher billet heating | 2,200 | Nat. gas | 1,014 | 8,200 | 6 | 18 | — |
| Batch forging | 2,200 | Coke oven gas | 26 | 42,000 | $1\frac{3}{4}$ | 9 | 5 |

ing doors at the ends and the combustion chambers under the hearth is 380 sq ft. Then the maximum rate of heat liberation is

$$\frac{10{,}000 \text{ cu ft per hr} \times 1000 \text{ Btu per cu ft}}{380 \text{ sq ft}} \quad 26{,}000 \text{ Btu/sq ft/hr}$$

and the average rate while heating up will be about 20,000 Btu per sq ft hourly. From the curves of Figure 16 by interpolation, the time will be about $2\frac{1}{2}$ hours.

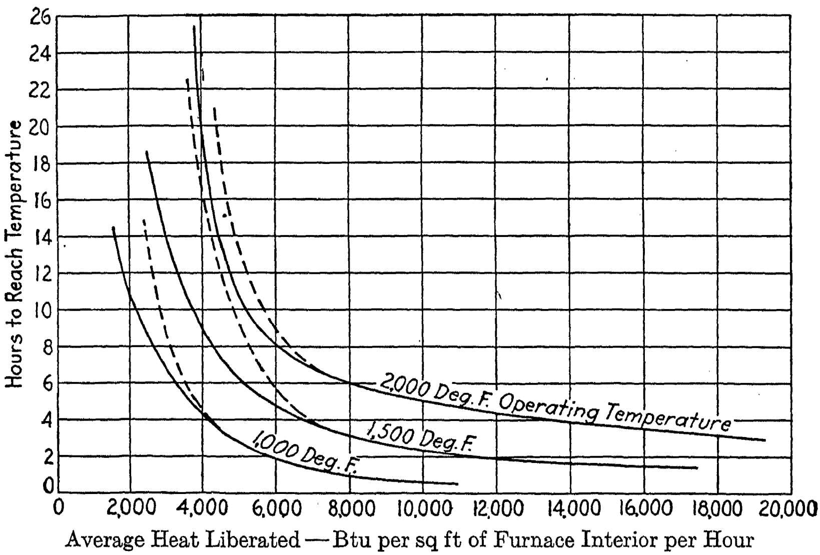



Figure 16. Dotted lines show that heating up the furnace with constant heat input, instead of great heat input at start, takes more heat hourly for the same total time or a longer time for the same hourly heat input.

The effect of the rate of heat liberation is indicated by the commercial furnace tests of Table 18, where the chain hearth furnace and the tunnel kiln required 11 hours and 23 hours respectively to heat, on account of a low rate of heat liberation. The comparative economy at different rates may be obtained from Figure 16 and tabulated as in Table 19, which is for furnaces at 1500 deg F. From this tabulation the most efficient rate of heat liberation is 12,000 Btu per sq ft hourly.

Table 19. Total Heat Required

| Rate of heat liberation (Btu sq ft hourly) | Hours to heat, from Fig. 16 | Total heat used (Btu per sq ft) |
|---|---|---|
| 2,000 | 23 | 46,000 |
| 4,000 | 9 | 36,000 |
| 6,000 | 5 | 30,000 |
| 8,000 | 3.2 | 25,600 |
| 10,000 | 2.5 | 25,000 |
| 12,000 | 2.0 | 24,000 |
| 14,000 | 1.8 | 25,200 |
| 16,000 | 1.6 | 25,600 |
| 18,000 | 1.5 | 27,000 |

As another example, consider the case of the chain hearth furnace in Table 18. This furnace required 11 hours with a low heat liberation average of 3500 Btu per sq ft of furnace interior hourly. The maximum demand in this furnace when heating a maximum of 900 lbs of steel per hour is 900 cu ft of natural gas per hour and the inside area is 228 sq ft. The burner capacity is 1200 cu ft per hour, or a maximum liberation of 5300 Btu per sq ft per hour.

For 11 hours and 3500 Btu per sq ft per hour, corresponding to a consumption of 800 cu ft of gas per hour, the gas used was 8800 cu ft. At maximum burner capacity with 5300 Btu per sq ft liberated per hour, the time to heat up is 6 hours and the total fuel is 7200 cu ft. Now, if additional burners were installed to be used only for heating up, and with a capacity such that the maximum input was 2750 cu ft per hour, or 12,000 Btu per sq ft per hour liberated, the time would be 2 hours and the total gas used would drop to 5500 cu ft. This is a saving of 1700 cu ft and the economy accomplished by the additional burners will depend upon the number of times the furnace is heated from cold in a year.

Intimately connected with the question of whether or not a furnace is heated up quickly is the amount of heat stored in the refractory lining, as measured by the temperatures through the thickness of the lining. With the thought of having a numerical idea of this heating in addition to the testimony and judgment of visual inspection, records of wall temperatures were made for the tests on which this discussion is based.

Three different wall constructions present in the test furnace were selected, and thermocouples were buried in these walls at different depths.

For each test a curve was plotted for the temperature distribution in each of the walls at the time that the furnace was considered as heated up, which are the times given in Figure 16.

Rather than reproduce these curves for each test, it was felt that the temperature taken from each curve at a point 2 in from the inside of the furnace would accurately express the relative heat storage in the walls. The heat stored beyond a depth of 2 in from the inside would be of little value in offsetting the drop tending to occur when a cold charge would be placed in the furnace. By dividing the temperature at 2 in depth by the final temperature of the furnace, a percentage is obtained which serves as a comparative index of the heat storage. The values of this percentage are given in Table 20.

Table 20. Effect of Wall Construction

| Wall: Firebrick (in) | Wall: Insulation (in) | Steady heat liberation (Btu per sq ft hourly) | Temperature at 2 in depth at different furnace temperatures | | | | % at different furnace temperatures | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1000 | 1200 | 1400 | 1600 | 1000 | 1200 | 1400 | 1600 |
| $4\frac{1}{2}$ | 10 | 3900 | 630 | 950 | 1220 | 1420 | 63 | 79 | 87 | 89 |
| | | 5830 | 530 | 740 | 980 | 1260 | 53 | 62 | 70 | 79 |
| | | 7800 | 320 | 500 | 740 | 1190 | 32 | 42 | 53 | 74 |
| 9 | 5 | 3900 | 620 | 900 | 1180 | 1360 | 62 | 75 | 84 | 85 |
| | | 5830 | 520 | 720 | 900 | 1200 | 52 | 60 | 64 | 75 |
| | | 7800 | 300 | 495 | 750 | 1150 | 30 | 41 | 54 | 72 |
| $13\frac{1}{2}$ | $2\frac{1}{2}$ | 3900 | 640 | 940 | 1220 | 1400 | 64 | 78 | 87 | 88 |
| | | 5830 | 520 | 740 | 1000 | 1220 | 52 | 62 | 72 | 76 |
| | | 7800 | 300 | 500 | 760 | 1150 | 30 | 42 | 54 | 72 |

Examination of Table 20 indicates that practically no difference exists in the heat-storage values for the different wall thicknesses given, which includes the majority of furnace walls. The close agreement in these heat penetration figures for the different times of heating with different rates of firing demonstrates that the heating of a furnace is practically independent of wall construction when the walls are of firebrick and insulation combinations (not including light refractories). This has already been indicated by the agreement in performance of different commercial furnaces of widely different wall constructions with the curves derived from tests in the experimental furnace.

Also it was found that tests with variable fuel rates gave the same values as Table 20 for the same average rates of heat liberation.

A number of interesting conclusions may be outlined on the basis of the data developed in these tests. The principal conclusions may be outlined as follows:

(1) An industrial furnace to be operated at an average temperature of 1600 deg F is "heated up" when the temperature of the lining at a depth of 2 in from the inside is 75 per cent of the furnace temperature.

(2) The time required to heat up depends upon the rate of firing and the final temperature required.
(3) The time required for the same rate of firing and the same final temperature is practically independent of the wall construction and amount of insulation, as already stated in the discussion of radiation and absorption.
(4) A variable rate of firing, with the highest rate at the beginning of the heating-up operation, is more efficient than a constant rate equal to the average of the variable rate.
(5) The most efficient average rate of firing for the variable rate method of heating up expressed in Btu liberated hourly in the furnace per sq ft of interior area of refractory lining, is about 12,000 Btu.
(6) In some gas-fired furnaces, the installation of burners, to be used only when heating up, will save time and fuel during heating-up periods.
(7) With a knowledge of fuel rates most desirable when lighting, burners may be more intelligently selected for fuel-fired furnaces.

The foregoing conclusions are for various firebrick walls with different combinations of backing-up insulation, and are not applicable to walls of light insulating firebrick. These bricks, weighing about 3 pounds and capable of withstanding temperatures up to about 2500 deg F, will reduce the heating time to about one-half of that with any firebrick and insulation construction. This material is discussed in greater detail in Chapter 6.

As an example of the application of the information in Figure 16 to the estimating of burner capacity, consider a furnace with inside dimensions of 4 ft $\times$ 4 ft $\times$ 20 ft long, or a total inside area of 352 sq ft, with an operating temperature of 1500 deg F. For the great majority of industrial furnaces, the proper burner capacity for operation will heat the furnace from cold to operating temperature in from 3 to 6 hours, assuming a firebrick lining, with the average time for all furnaces about 4 hours. Using 4 hours in this case, the heat liberation required from Figure 16 is 7000 Btu per sq ft of interior per hour, and the total burner capacity is 2,464,000 Btu per hour. If the fuel is natural gas, the burner capacity will be about 2500 cu ft per hour, and if the fuel is oil, the burner capacity required is about 18 gallons per hour.

This calculation, using a heating-up time of 4 hours, is for the average furnace operation. When a furnace is to be operated continuously for long periods of time, burner capacity obtained by this assumption will be somewhat large, and a heating-up time of 6 hours should be assumed. The individual calculation at the beginning of this chapter for the same furnace showed a requirement of 1370 cu ft of natural gas per hour, average for continuous production; and under these conditions a burner capacity of 2500 cu ft of natural gas per hour is possibly slightly greater than necessary

for control. Using 6 hours, the heat liberation required is 5200 Btu per sq ft per hour from Figure 16, and the burner capacity is 1830 cu ft of natural gas per hour, which would be minimum for this furnace. The other extreme is the case where a furnace is to be heated with its charge to temperature in the shortest possible time. In such cases, an assumption of 3 hours to heat up and the use of this assumption in Figure 16 will give a higher burner capacity than is indicated for average conditions.

This method as outlined is very rapid and satisfactory for estimating burner sizes, and is also useful as a check on more elaborate calculations where extreme accuracy is necessary.

## Fuels and Combustion Data

A tabulation of useful data pertaining to the combustion of the common industrial fuels is given in Table 21. In addition to the usual combustion data, this tabulation includes the combustion efficiency at 2000 deg F for each fuel, which is frequently neglected in a comparison of fuels. This combustion efficiency is the percentage of the heating value of the fuel which remains for useful work after subtracting the sensible heat in the flue gases from the heating value. Variation in this value is most pronounced in those fuels which have a low heating value and considerable quantity of flue gases to be heated.

In connection with the handling of low-pressure air and gases to industrial furnaces in the mills, it is frequently desirable to obtain rough measurements of flow through thin-plate orifices, and a formula for this flow is of value. The subject of flow through orifices is extremely complicated where a high degree of accuracy is required, but for most mill requirements such accuracy is not necessary. The following formula will give the flow, where the drop through the orifice does not exceed 10 per cent of the upstream pressure:

$$V = 23{,}650\, KA\sqrt{\frac{HP}{DT}}$$

where $V$ = cu ft per minute of gas or air at 60 deg F and 14.7 lbs per sq in absolute pressure

$K$ = 0.6 average orifice coefficient for thin plate orifice

$A$ = area of the orifice in sq ft

$H$ = pressure drop across the orifice in inches of water

$P$ = downstream pressure in lbs per sq in absolute pressure

$D$ = specific gravity of gas at 60 deg F (air is 1.0)

$T$ = temperature of the air or gas, deg F absolute

The efficient utilization of by-product fuels has become one of the major problems of the steel industry, and general information concerning some of these fuels is not out of place at this point. It has been stated* that in 1937 the heat in by-product gases produced by the steel industry in the

* Fox, E. G., and Clemmitt, W. B., *A.S.M.E. Transactions*, November, 1939.

United States was equivalent to 32 million tons of coal, or about 7 per cent of the national coal consumption.

Coke-oven gas contains about 25 per cent of the heat in the coal from which it is made, and is produced at a very uniform rate from a large battery of ovens in continuous operation of seven days per week and 24 hours a day. The gas is delivered at pressures up to 5 pounds per sq in (average $2\frac{1}{2}$ lbs per sq in) and contains some tar and dust unless especially cleaned. It also contains a considerable quantity of moisture, and the sulfur content is from 500 to 600 grains per 100 cu ft. Preheating of the gas above 500 deg F will cause a breakdown of hydrocarbons and deposition of soot, but sufficiently high flame temperatures for all purposes may be obtained without preheating of the gas. Preheating of combustion air is not necessary for any steel mill operation except melting, but may be used for purposes of economy. In the case of open-hearth firing, fuel oil or tar is usually used in conjunction with coke-oven gas to supply luminosity to the flame, in order to prevent the excessive brick temperatures which result with the use of the transparent flame of coke-oven gas alone. The gas can be transported in relatively small pipes and is of great value in most of the heating operations. The only exception is where decarburization of the steel is an important factor, as discussed in the preceding chapter (Table 1).

Blast-furnace gas has recently assumed increased importance as the result of the advantages found in the mixing of this gas with coke-oven gas, and from the use of this gas alone in certain applications, such as the firing of the coke ovens to conserve coke oven gas. This gas contains about one-half of the heat in the coke used in the blast furnace, and the supply is not always continuous, due to delays and shut-downs of a small number of blast furnaces. An additional disadvantage is the fact that the gas cannot be conveniently stored on account of the low heating value and consequent large volume. The gas is usually delivered at a pressure between 2 and 6 inches of water, and contains considerable dirt (8 to 12 grains per cu ft for raw gas) and moisture. The dust content for ordinary wet cleaning is about 0.25 grain of dust per cu ft of gas, and from cyclone towers it is about 0.10 grain per cu ft. By further cleaning it is possible to reduce the dust content to less than 0.01 grain. Where blast-furnace gas is used by itself for temperatures above 1500 deg F, preheat of both gas and air is commonly applied, but by mixing 60 per cent or more of coke-oven gas with the blast-furnace gas, temperatures of 2500 deg F can be maintained without preheat of either gas or air. The distribution of blast-furnace gas is complicated by the necessity for large pipes.

Producer gas is made from both bituminous and anthracite coal, as well as from coke. Anthracite gas has claimed increasing attention in recent years because of its cleanliness and consequent ease of control.

Table 21.

| Fuel | Average chemical analysis (% by wt for solids and liquids; by vol for gases) S | H₂ | C | N₂ |
|---|---|---|---|---|
| Coke | 1.0 | | 85.7 | |
| Anthracite | 0.5 | 2.4 | 84.6 | 0.9 |
| Lignite | 0.9 | 6.8 | 41.3 | 0.7 |
| Sub-bituminous | 0.6 | 5.9 | 60.1 | 1.0 |
| Bituminous coal | 0.6 | 5.2 | 78.0 | 1.3 |
| Semi-bituminous | 0.5 | 4.8 | 84.6 | 1.0 |
| Cannel coal | 1.0 | 6.8 | 73.3 | 1.3 |
| Fuel oil 24 Bé | 0.5 | 13.0 | 83.2 | 2.0 |
| Coal tar | 0.8 | 6.0 | 86.7 | 0.1 |
| Pitch (topped tar) | | | | |
| Natural gas | | | | 5.0 |
| Coke oven gas | | 53.0 | | 12.1 |
| Blast furnace gas | | | | 65.0 |
| Bituminous producer gas | | | | |
| Hot | | 12.5 | | 56.5 |
| Cold | | | | |
| Anthracite producer gas | | | | |
| Hot | | 16.5 | | 50.2 |
| Cold | | | | |
| Butane | | | | |
| Propane | | | | |
| Coal gas | | 47.0 | | 2.3 |
| Blue water gas | | 52.9 | | 4.7 |
| Carburetted water gas | | 35.2 | | 1.8 |
| Oil gas | | 58.4 | | 3.8 |
| Still gas | | | | |

* Units are lbs for solid fuels, gallons for liquid fuels,

| Fuel | Density standard conditions, (lbs per unit) | Cold combustion air, perfect combustion (cu ft per unit) |
|---|---|---|
| Coke | 30 (piled) | 128 |
| Anthracite | 55 | 139 |
| Lignite | | 71 |
| Sub-bituminous coal | 40 | 103 |
| Bituminous coal | to | 137 |
| Semi-bituminous coal | 50 (piled) | 148 |
| Cannel coal | | 139 |
| Fuel oil 24 Bé | 7.55 | 1410 |
| Coal tar | 9.49 | 1500 |
| Pitch (topped tar) | | |
| Natural gas | 0.0491 | 10.11 |
| Coke oven gas | .0288 | 4.08 |
| Blast furnace gas | .0767 | 0.66 |
| Bituminous producer gas | | |
| Hot | .0674 | 1.07 |
| Cold | | |
| Anthracite producer gas | | |
| Hot | .0685 | 1.05 |
| Cold | | |
| Butane | .148 | 30.47 |
| Propane | .116 | 23.82 |
| Coal gas | .0313 | 4.64 |
| Blue water gas | .0342 | 2.35 |
| Carburetted water gas | .0454 | 4.88 |
| Oil gas | .0226 | 4.23 |
| Still gas | .0743 | 15.60 |

Combustion Constants for Fuels

| | $CH_4$ | $C_2H_6$ | $C_2H_4$ | CO | $CO_2$ | Ill | Ash | Heating value (Btu per unit*) Net | Gross |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 13.1 | | 12,500 |
| 1.5 | | | | | | | 10.1 | | 14,070 |
| 40.7 | | | | | | | 9.6 | | 7,189 |
| 27.0 | | | | | | | 5.4 | | 10,557 |
| 11.5 | | | | | | | 3.4 | | 14,134 |
| 5.1 | | | | | | | 4.0 | | 14,669 |
| 8.3 | | | | | | | 9.3 | | 14,251 |
| 1.3 | | | | | | | | 140,000 | 147,000 |
| 3.1 | | | | | | | | 150,000 | 159,000 |
| | | | | | | | | 165,000 | 173,000 |
| | 80.3 | 14.7 | | | | | | 970 | 1,070 |
| | 28.1 | | | 6.0 | 0.8 | | | 425 | 480 |
| 0.1 | | | | 27.8 | 7.1 | | | 90 | 92 |
| | 3.0 | | | 20.5 | 7.5 | | | 138 | 148 |
| | | | | | | | | 128 | 137 |
| | 1.2 | | | 24.0 | 7.5 | | | 144 | 153 |
| | | | | | | | | 134 | 143 |
| $C_4H_{10}$ — 93.0; $C_3H_8$ — 7.0 | | | | | | | | 2,977 | 3,225 |
| | | $C_3H_8$ — 100.0 | | | | | | 2,371 | 2,572 |
| | 34.0 | | 6.6 | 9.0 | 1.1 | | | 482 | 540 |
| | 2.2 | | | 36.8 | | 3.4 | | 287 | 315 |
| | 14.8 | | 12.8 | 33.9 | 1.5 | | | 535 | 579 |
| | 28.8 | | | 4.4 | 1.2 | 3.4 | | 440 | 493 |
| | 48.4 | 22.5 | 3.0 | $C_3H_6$ — 6.3; $C_3H_8$ — 12.8; $C_4H_{10}$ — 7.0 | | | | 1,517 | 1,658 |

and cu ft for gaseous fuels.

| Cold flue ases (cu ft per unit) | Density of flue gases (lbs per cu ft) | Combustion efficiency at 2000 deg F (% of net heating value) | Ultimate $CO_2$ | Flame temperature, corrected for dissociation (deg F) | Sulfur (lbs per million net Btu) |
|---|---|---|---|---|---|
| 128 | 0.0835 | 59.0 | 20.8 | | 0.80 |
| 140 | .0820 | 60.5 | 19.0 | | 0.35 |
| 82 | .0760 | 54.3 | 16.1 | | 1.25 |
| 112 | .0782 | 57.5 | 17.0 | | 0.57 |
| 143 | .0790 | 59.5 | 17.4 | | 0.43 |
| 153 | .0795 | 58.2 | 17.5 | | 0.34 |
| 146 | .0782 | 59.0 | 16.0 | | 0.70 |
| 1505 | .0760 | 51.5 | 13.4 | 3600 | 0.27 |
| 1560 | .0785 | 53.5 | 16.7 | | 0.51 |
| 11.19 | .0730 | 49.2 | 12.1 | 3600 | |
| 4.79 | .0708 | 49.5 | 11.0 | 3640 | 1.41 |
| 1.52 | .0830 | 25.2 | 23.8 | 2700 | |
| 1.91 | .0780 | 40.5 | 19.0 | 3130 | 0.80 |
| | | | | 2630 | 0.40 |
| 1.82 | .0780 | 43.5 | 19.5 | 3000 | 0.70 |
| | | | | 2500 | 0.35 |
| 32.93 | .0755 | 51.2 | 14.0 | 3640 | |
| 25.99 | .0750 | 51.6 | 13.7 | 3660 | |
| 5.41 | .0720 | 49.6 | 10.7 | 3610 | |
| 2.87 | .0740 | 55.0 | 22.3 | 3800 | |
| 5.54 | .0750 | 52.5 | 17.2 | 3800 | |
| 4.88 | .0705 | 50.0 | 10.7 | 3700 | |
| 17.00 | .0744 | 49.7 | 10.9 | | |

Figure 17 shows a producer installation for producer gas made from either anthracite or coke. The sulfur content of the original coal divides about evenly between the gas and the ash, and washing of the gas reduces the sulfur content another 50 per cent. Hot, unwashed gas from bituminous coal contains about 60 to 80 grains of sulfur per 100 cu ft; hot gas from anthracite contains about the same sulfur, and cold-washed gas from either coal has a sulfur content of from 30 to 40 grains per 100 cu ft.

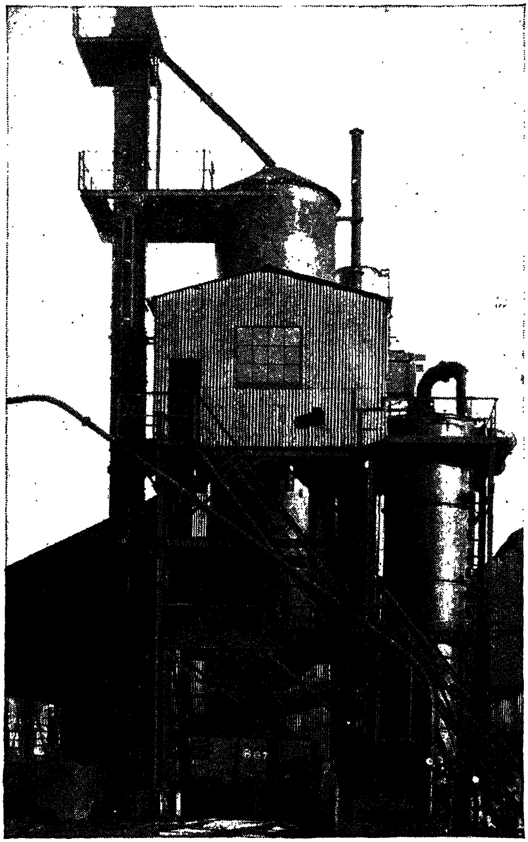


Figure 17. Producer to make gas from anthracite or coke.

Producer gas may be made from buckwheat or rice anthracite or from coke in the same producer. A conservative production rating of a 10-ft diameter producer operating on these fuels is 1600 pounds of rice anthracite per hour, 1850 pounds of #1 buckwheat anthracite per hour, and 2400 pounds of pea coke per hour (6000 lbs of bituminous coal can be gasified in a 10-foot producer).

The net heating value of hot gas made from coke is about 132 Btu per

cu ft, compared with 144 Btu per cu ft for gas made from anthracite. The cold gas made from either anthracite or coke may be used satisfactorily in furnaces up to 2400 deg F without any preheating of the combustion air, and the speed of heating will compare directly with that obtained with other fuels. Hot gas will operate at somewhat higher temperature, and with 600 deg F preheat of the combustion air it has been possible to operate at 2760 deg F with coke producer gas.

All forms of producer gas yield a higher percentage of flue gases per unit of heat developed, and in comparing the cost of producer gas with that of other fuels, it is important to consider the cost of the fuel in the furnace, as shown in Table 23, rather than the cost of fuel at the burner, which does not include the effect of the relative amounts of flue gas.

Producer gas made from anthracite or coke is usually piped in spiral-welded steel pipe without any refractory lining, which is ordinarily coated on the inside to prevent corrosion of the pipe by the gas.

Butane and propane are by-products of the production of gasoline, and are shipped in liquid form under pressure. The liquid is released from this pressure and vaporized by controlled steam heat at the point of use, when it becomes a gaseous fuel which is handled in pipes to the furnaces in the usual manner.

One of the effects of the current war has been the increasing interest in the utilization of pulverized coal in metallurgical furnaces, to conserve fuel oil and natural gas. The use of pulverized coal for this purpose is not at all new, but to date the application has been limited on account of difficulties with the fly ash which results from the combustion of pulverized coal. Where the furnace operating temperature is below the softening point of this ash, the ash will be in dry, powdery form and will adhere lightly to the furnace lining. This must be removed at intervals of about one week. Also, this dry ash leaving the furnace through openings and flues must be collected by exhaust ducts and fans and removed from the building. For furnace operations above about 2200 deg F, care must be taken in the selection of the coal to avoid wet ash, which will adhere tightly to both the furnace lining and to the heated product.

In the consideration of pulverized coal, the author believes that furnaces should be divided as follows:

(1) All heat-treating furnaces requiring close control, where pulverized coal should be avoided.

(2) Rolling-mill furnaces, where the application should be carefully considered, with attention to operating temperatures, coal available, and effects on the product.

(3) Forging furnaces and other types of large size and for temperatures between 1800 and 2200 deg F, where pulverized coal has been proved satisfactory as a substitute for other fuels.

Pulverized coal systems may be of the storage or recirculating types. With the storage system, the coal is pulverized as required and transferred by compressed air to storage bins adjacent to the individual furnaces. With the recirculating system, the pulverized coal is carried by low pressure air (25 to 30 per cent of the total air required for combustion) through a pipe which returns to the pulverizer after supplying the furnaces on the line, in the same manner as in a fuel-oil system. The pulverizer must be of sufficient capacity in this case to supply the maximum demand, and is arranged to adjust automatically the pulverizing rate to the demand of the furnaces supplied. A recent development is the unit pulverizer of the circulating type, with a separate unit for each furnace.

Another development which has been accelerated by the increased demand for fuel oil and natural gas is so-called colloidal fuel. This term is applied to a mixture of pulverized coal and fuel oil; the mixture is treated to keep the coal in suspension in the fuel oil. Oil membranes are thought to surround the coal particles and to hold them in place, thus giving the mixture its colloidal properties. Initial attempts to maintain the coal in suspension by chemical methods do not appear to be satisfactory, and the more generally accepted means at this date is the treatment of the mixture in a colloid mill, where the coal and oil are forced through very small apertures between a stationary and rotating plate.

Best results to date have been obtained with a mixture containing 40 per cent coal by weight and 60 per cent fuel oil, usually of the Bunker C grade. The coal is first pulverized to such fineness that about 85 per cent will pass through a 200-mesh sieve. The pulverized coal is then mixed with the oil and the mixture forced at about 10 pounds per sq in pressure through the colloid mill. The resulting fineness is reported to be such that it is equivalent to about 90 per cent passing through a 400-mesh sieve. The resulting colloidal fuel is pumped through a distributing system in every way the same as that used for fuel oil.

Colloidal fuel is heavier than fuel oil, weighing about 10 pounds per gallon, and contains about 170,000 Btu per gallon. It is more corrosive to burner and pump parts than oil, requires increased power for pumping, and will increase the difficulties with clogging of small screens and burner openings. The flame temperature is somewhat higher than that obtained with Bunker C fuel oil.

With coal containing 7 per cent ash and mixed in the proportion of 40 per cent by weight, the colloidal fuel contains about 3 per cent of ash. However, it is claimed that the degree of fineness of this fuel is so great that this amount of ash is not objectionable and that it will not adhere to the furnace lining.

In order to create a premium colloidal fuel, almost free from ash, a method has been devised, but not yet tried in commercial operation, in

which the coal is chemically converted to carbon by treatment with air and acid. The resulting solid carbon, containing less than 1 per cent ash, is mixed with oil on the basis of 40 per cent by weight, and the mixture is passed through a colloid mill to produce a fuel containing less than 0.5 per cent ash. This fuel would be preferable from the standpoint of burner difficulties, but it is obtainable only at some as yet unknown increase in cost.

## Burners for Various Fuels

**Gas Burners.** In discussing the different types of burners it is desirable to divide them into those intended for clean gases and those intended for dirty gases. Clean gases in this division include natural gas, coal gas, water gas, anthracite or coke producer gas (scrubbed), butane, propane, and still gas (from oil refinery stills). Dirty gases include coke-oven gas (as used in the steel mills), blast-furnace gas in its usual form, and hot producer gas.

A burner for any fuel is not actually the "burner" of the fuel, but a mixer to prepare the fuel for burning in the desired manner. The variation in this desired manner of burning accounts for the variety of gas burners available; they are classified in Table 22, which also includes burners for liquid fuels.

Figure 18 is a diagrammatic representation of the principles and arrangements of burners and control for gaseous fuels. (See also Control of Atmosphere in Chapter 3.)

Blast-type burners are generally the simplest. In these, the air and gas are mixed in a cast-iron body and the mixture is fired through an open hole in the furnace wall. In most furnace applications of this type of burner, some air is introduced through the furnace opening in spite of shutters or other devices, and close control of the furnace atmosphere is difficult. Air-gas ratio is controlled manually by adjustment of the air and gas valves to the burner, or automatically by any of the methods described in the next chapter. Various designs of nozzles are available for length and type of flame, self-piloting, and for other purposes. The principal use of these burners is for clean and dirty gases in combination with oil, conversion from oil at minimum expense, and the firing of high-temperature furnaces where atmosphere control is not of extreme importance. Figure 19 shows a typical blast-type burner.

Nozzle mixing-type burners are generally described as a variation of the blast-type. These are sealed into the furnace wall and are arranged internally for parallel flow of air and gas. This arrangement produces slow mixing and relatively long flame. The atmosphere in the furnace is controlled better than with blast-type burners because of the sealed setting in the furnace wall. Since there are no small ports in this type of burner it is

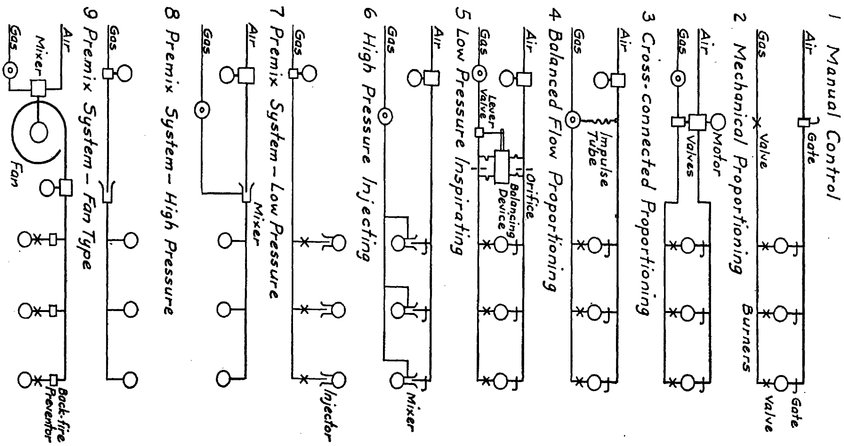


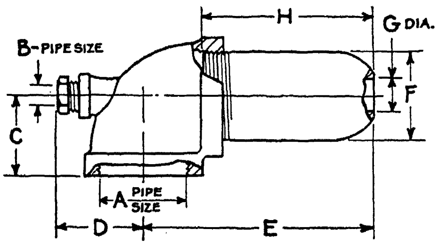

Figure 18. Co on burner syste

Table 22. Burners Commonly Used on Industrial Heating Furnaces

| Gas burners | Description | Make | Fuel | Pressure | | Uses |
|---|---|---|---|---|---|---|
| | | | | Fuel | Air | |
| 1. Two Pipe<br>A. Nozzle Mix (Turbulent) | See Fig. 19 | Home-made, No. Amer. Elbow, Bloom Nozzle Mix | All gases, including raw bituminous producer gas | 3–8 oz. | 2–16 oz | Obsolete but ideal for some special uses — forge furnaces for minimum decarb; anthracite or coke producer gas. |
| B. Nozzle Mix (Parallel Stream) | See Fig. 20 | Eclipse ZB, Economix | All gases except raw bituminous producer gas | 3–8 oz. | 2–16 oz | Sizes to 3 million Btu per hr for max. turndown at min. cost where conditions are constant. Also for dirty gases. |
| C. Luminous (Combination — Parallel or Turbulent) | See Fig. 21 | Bloom, Continental, P.I.E. | All gases except raw bituminous producer gas | 3–8 oz | 1–8 oz | Same as N. M. Parallel except for larger capacity. Velocities under 20 fps for true luminosity. Can be adjusted to premix. |
| 2. Inspirating (Low Pressure) | See Fig. 22 | Surface Combustion, Eclipse LWP & HWP, No. Amer. Aspirator | Clean gases only | Zero | 8–16 oz | For heat treating where atmosphere is important. |
| 3 Injecting (High Pressure) | See Fig. 23 | Surface Combustion, Eclipse MS & NT, No. Amer. Hi. Press. | Clean gases below 1500 Btu/cf not butane and propane | Below 750 Btu 5–25 psi<br>Above 750 Btu 10–25 psi | Atmosphere | For heat treating where atmosphere is important and back pressure under .05 in $H_2O$ Gas under 1500 Btu/cf. |
| 4. Premix<br>A. Ribbon<br>B. Metal Spud<br>C. Refractory Spud<br>D. Open Nozzle<br>E. Closed Nozzle | | Types A, B, C by Eclipse, Maxon, No. Amer. Type D — Eclipse Ferrafix and Sticktite Type E — N.A. Tunnel, Eclipse LBA and HBA and Midget Wallite | Clean gases only | 1–16 oz mixture | Depends on mixer. | Ovens-Furnaces where multiplicity of burners is indicated. |
| Oil burners | | | | | | |
| 1. Low Pressure Air Atomization | | | Oil usually under 20 gph | 5–40 psi | 8–16 oz | For light oil to 20 gph and heavy oil to about 10 gph. |
| 2. Steam or High Press. Air Atomization | | | All oils above about 20 gph and tar | 10–60 psi | 40–100 psi steam or primary air. Secondary air 0–8 oz | For all oil above about 20 gph and where blower air is not available. |

ideal for use with reasonably dirty gases, such as the usual coke-oven gas. The long flame and absence of localized heat also make this a desirable burner for use with the enclosed combustion chambers of underfired furnaces. Another common application is in forging furnaces, particularly those with long chambers. Figure 20 illustrates this type of burner.

Radiant, luminous, or diffusion burners are those in which the air and gas are also arranged in parallel streams, as in the nozzle-mixing burners, but at lower velocities and with provision for the cracking of the gas before combustion. The characteristics are long flame and a high degree of




GAS AND AIR FORM A PARTIAL PREMIX WITHIN THE ELBOW TYPE GAS BURNER WITHOUT BACK PRESSURE ON THE GAS. THEY CAN BE USED FOR OPEN FIRING THROUGH BURNER PORTS WITH POSSIBLE MAXIMUM MIXTURE PRESSURES NEARLY EQUAL TO THE AIR PRESSURES USED.

ELBOW TYPE BLAST BURNERS

CAPACITIES OF BURNERS IN $\frac{\text{B.T.U.}}{1000}$ PER.HR. WITH GAS AT 3 OZ.MIN.

| BURNER SIZE | DIMENSIONS IN INCHES | | | | | | | | PRESSURE IN OUNCES | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 |
| | $1\frac{1}{2}$ | | | $2\frac{1}{4}$ | | | | | 150 | 210 | 260 | 300 | 335 | 370 | 400 | 410 |
| | | | | $2\frac{1}{2}$ | | | $1\frac{1}{4}$ | $3\frac{7}{8}$ | 240 | 340 | 415 | 480 | 530 | 580 | 635 | 680 |
| | | | $2\frac{3}{4}$ | | $6\frac{5}{8}$ | $2\frac{7}{8}$ | $1\frac{1}{2}$ | | 350 | 500 | 600 | 700 | 780 | 860 | 930 | 1000 |
| | | | | $3\frac{3}{8}$ | $7\frac{1}{4}$ | | | | 475 | 675 | 825 | 950 | 1060 | 1150 | 1250 | 1350 |
| | | | | | $8\frac{1}{2}$ | | | | 700 | 1000 | 1200 | 1400 | 1560 | 1700 | 1860 | 2000 |
| | | | | $6\frac{3}{8}$ | 12 | | | | 1400 | 2000 | 2400 | 2800 | 3100 | 3400 | 3700 | 4000 |

Figure 19. Typical blast-type gas burner.

luminosity. These burners are adjustable from this mixing to turbulent mixing and are ideal for high-temperature furnaces of capacities above those served by the nozzle-mixing burners. Figure 21 shows an example of this type.

Low-pressure premix burners are illustrated in Figure 22. They provide one of the best controls of furnace atmosphere that can be obtained in the combustion of gas. The passage of low-pressure air through the mixer, which is part of the system, inspirates gas at zero pressure in direct proportion to the air flow, and insures an excellent control of the air-gas ratio. Where individual control of heat at each burner is essential, a mixer must be provided at each, but in many cases one mixer may serve several burners with a single control of heat (by control of air at the mixer) for the group (Figure 18). The mixture (or manifold) pressure at the burner of the air-gas mixture is generally a number of inches of water equal to one-half

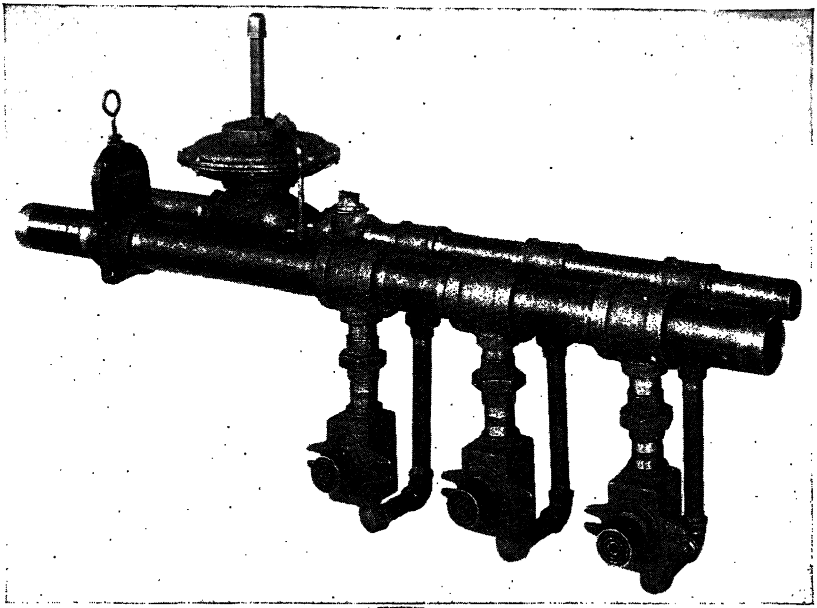


Figure 20. Nozzle-mixing burners with air-gas ratio control.

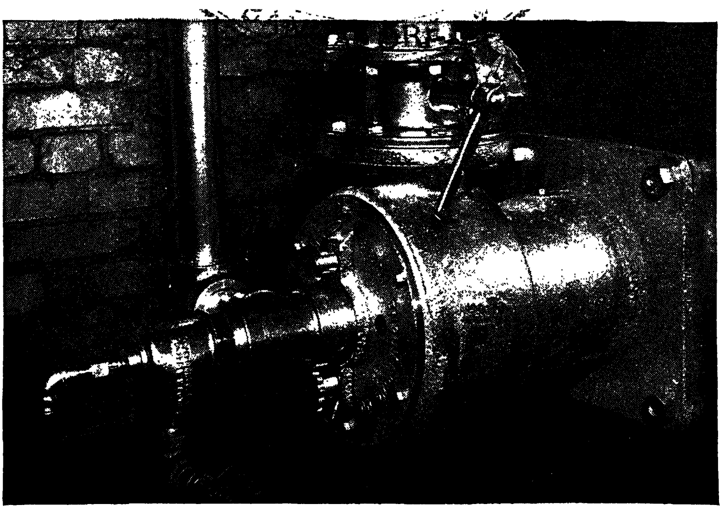


Figure 21. Long-flame gas burner.

the number of ounces of air pressure to the mixer. With the high degree of mixing from these burners the flame is short and hot and generally transparent for most gases. A group of small burners is usually preferable to one large one, in order to insure the maximum of temperature uniformity in the furnace. For high temperatures, alloy burner tips and sillimanite burner blocks must be used for long life.

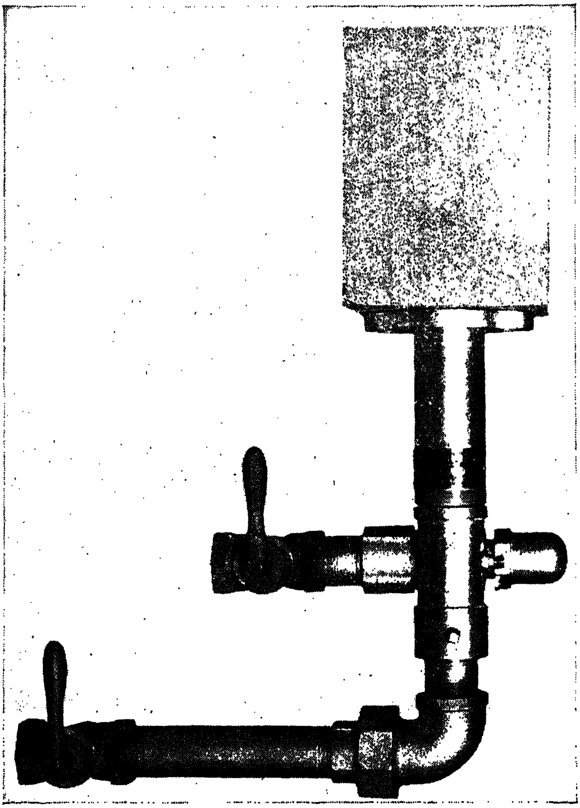


Figure 22. Low-pressure premix gas burner.

The turn-down, or reduction in flow without back-firing, for low-pressure premix burners depends upon the gas to be burned and upon the initial air pressure to the mixer. For example, the minimum mixture or manifold pressure for natural gas is 0.3 in of water and the maximum mixture pressure with 12 ounces air pressure to the mixer is 6.0 in of water. Since the flow varies with the square root of the pressure, the turn-down is $\sqrt{6.0}/\sqrt{0.3}$ which is 4.45 to 1.0. Minimum mixture pressures for other gases are 0.5 in of water for manufactured gas (coal gas), 1.0 in of water for water gas, and 0.2 in of water for anthracite producer gas.

High-pressure injecting burners (Figure 23) are those in which the gas injects the air for combustion from the atmosphere. The gas pressure (energy available for injection) required depends upon the amount of air to be injected. For natural gas (10 parts of air required for each part of gas by volume) the minimum pressure for good operation in closed furnaces is 15 lbs per sq in; for manufactured gas (5 parts of air) the minimum pressure is about 10 lbs; and for anthracite producer gas (about 1 part air) it is 1 lb per sq in.

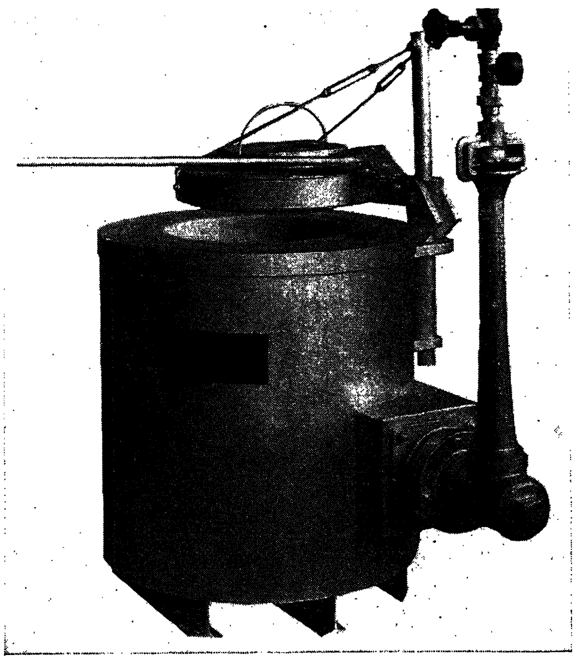


Figure 23. High-pressure injector gas burner on pot furnace.

For natural gas and for all other gases requiring above 7 parts of air to 1 part of gas, the burners should be arranged with two stages of injection for good control of furnace atmosphere, while a single stage of injection is sufficient for leaner gases. The burner arrangement may be separate injecting burners for individual control, or a number of tunnel burners supplied with air-gas mixture from one injector.

The high-pressure gas burner is a simple type where sufficiently high gas pressures are available, and it is satisfactory for most applications. Exceptions are where the furnace pressure is very high and where unusually accurate control of furnace atmosphere is required. An example of the first exception is at the top of high furnaces, and the reason for the second

exception is that variation in the amount of injected air may be caused by variations in furnace pressure.

Burner pressure in high-pressure burners is proportional to the gas pressure; the turn-down depends upon the fuel and upon the initial gas pressure. The minimum burner pressures without back-firing are the same as for the low-pressure burners already described. The following tabulation will show the turn-down for several gases and pressures, in closed furnaces and with theoretical air supply.

| Gas | Btu per cu ft | Gas pressure (lb per sq in) | Maximum burner pressure (in of water) | Minimum burner pressure (in of water) | Turn-down |
|---|---|---|---|---|---|
| Manufactured | 530 | 10 | 5 | 0.5 | 3.2 to 1.0 |
| Water gas | 310 | 7 | 7 | 1.0 | 2.7 to 1.0 |
| Natural | 1000 | 15 | 8 | 0.3 | 5.2 to 1.0 |
| Anthracite | 150 | 1 | 3 | 0.2 | 3.9 to 1.0 |

High-pressure gas burners are not used for butane or propane, because injection of the high ratio of air to gas necessary in these cases requires energy in excess of that produced by available gas pressure.

An idea of the variation in the relation of throat area to orifice area (spud area) in high-pressure gas burners for various gases may be gained from the facts that for natural gas the orifice should be 1/115 of the throat area; for manufactured gas the relation is 1/46, and for anthracite gas 1/2.7.

In general, burners for dirty gases must be of the blast or nozzle-mixing type to avoid small orifices and openings which would become clogged by dirt or tar.

In the case of coke-oven gas the principal difficulty is with water and tar. Water can be avoided by proper care of drains, but the tar content constitutes a real difficulty. This heavy tar is condensed from the gas in orifices, throats, and in other constrictions, and is difficult to remove except by live steam, benzine, or naphtha. Clogging of orifices in regulators makes it difficult to control the gas pressure or ratios of air to gas. For these reasons, blast burners, nozzle-mixing burners, or luminous-flame burners are the most satisfactory for coke-oven gas in its usual form.

The dirt in blast-furnace gas is mostly in the form of dust, and when very dirty the gas requires burners in which all openings are large and available for cleaning. The air-gas ratio for this gas is only 0.7 to 1.0, which permits the gas to be used for the injection of air if a gas pressure of about 6 ounces per sq in is available. Such an arrangement permits automatic air-gas ratio control, because zero governors are not required in the gas line, and is inexpensive because blowers are not required. If the gas is sufficiently clean, air can be used to entrain it, but in this case one volume of air must entrain 1.4 volumes of the gas; since the gas is heavier than air, the turn-down is somewhat limited.

The theoretical flame temperature of blast-furnace gas when not preheated is only 2700 deg F compared with 3600 deg F for coke-oven gas; but this figure is raised to 3200 degrees by preheating 1000 deg F and to 3750 by preheating 1750 deg F (preheating of gas only).

Hot bituminous producer gas is the dirtiest of all the industrial gaseous fuels, containing both dirt and tar in large quantities. For this fuel, blast burners with provisions for cleaning are the only possibility. Figure 24

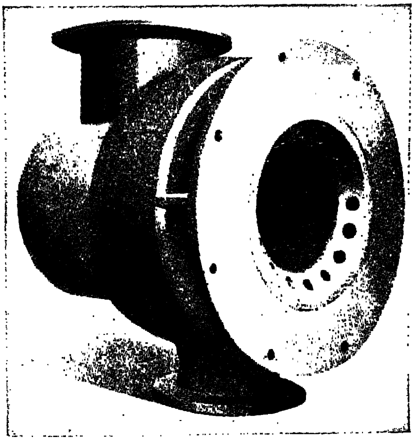


Figure 24. Type of large burner suited for dirty gases.

shows a Swiss burner for this fuel which is commonly used in Europe. European practice includes the use of a screw-operated blast gate for control, this gate being arranged with a knife edge for cutting the tar formed in the valve.

Bituminous producer gas leaves the producer at a low pressure of about 2 inches of water and is transported in large brick-lined mains to save heat in the gas. The velocity of hot gas in the mains should not exceed 30 feet per second. The tar content condenses rapidly at temperatures below about 900 deg F and solidifies at about 200 deg, which is an important reason for maintaining gas temperature to the furnace. Some idea of the pressure and temperature losses can be gained from the following data on several typical mains:

| Example | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Length (ft) | 130 | 100 | 130 | 60 |
| Inside diameter (in) | 63 | 54 | 54 | 54 |
| Gas (cu ft per hr) | 350,000 | 350,000 | 175,000 | 100,000 |
| Pressure drop (in of water) | 0.036 | 0.054 | 0.013 | 0.002 |
| Temperature drop (deg F) | 177 | 106 | 248 | 162 |

**Burners for liquid fuels.** The logical starting point in considering an oil-burning system is the storage tank. Books on storage tanks contain information on riveted tanks, electric welded tanks, horizontal and vertical

tanks, installation of tanks to pass Underwriters' specifications in different states, and so on. As this information is available from many sources it requires no repetition, but attention should be directed to the two most frequent mistakes; namely, the heating coils and the tank connections.

Steam coils should always be provided in a storage tank to keep the oil warm enough to pump easily. If the coils are too large, the heat in excess of that actually required will cause the oil to evaporate from the surface in surprisingly large quantities. If the coils are too small, the viscosity of the oil makes pumping it from the tank difficult and sometimes impossible. A good arrangement for average conditions consists of four lengths of $1\frac{1}{4}$-inch pipe the full length of the tank, arranged in series and reduced to $\frac{1}{2}$ inch at the inlet and $\frac{1}{2}$ inch at the outlet to take off condensation. The heating coils should be at the bottom of the tank and the steam outlet at the lowest point, so that the line will drain itself and prevent freezing.

The tank connections, in addition to the steam inlet and outlet, include oil inlet and outlet and vent pipe. The inlet line, through which the tank is filled, should always be at least 3 inches when a pump is used in filling, and 4 inches if it is necessary to depend on gravity. For unloading from a car, a rotary pump is ordinarily preferred, because the electric wiring is easier to install than are steam lines to a steam pump, and because there is less danger of freezing. A rotary pump will not lift more than about 5 feet of oil, while a safe suction lift of 18 feet can be figured with a steam pump. The oil outlet pipe should project through the top of the tank and should extend to within not less than 2 inches from its bottom. It is a good plan to set the tank slightly higher at the end opposite this connection so that it may be completely drained. The size of the outlet pipe can ordinarily be made the same as the suction inlet of the pump, except in the case of long distances, when the line should be made one size larger. It should never be made smaller, regardless of the fact that the pump may be oversize. The vent pipe should always be as large as the oil inlet, so that a dangerous pressure cannot be built up in case of overflow.

After leaving the tank, the oil should pass through double strainers which can be easily cleaned, and then into the pump. This pumping system may be either steam or electric. The advantages of either system are of minor importance. The chief argument in favor of the steam pump is that the steam pressure automatically varies with the load on the pump, so that the relief valve is assisted and its action is more sensitive; on the other hand, the electric pump has simpler packing and valves and is easier to maintain.

Whichever system is selected, it should be complete with relief valve, air chamber, and gage. The relief valve should be of the same size as the relief connection and should always be piped directly to the tank. It is frequently found that this pipe is connected into the suction line and that

the operation is unsatisfactory because gas or air has been trapped in the delivery line and is carried around indefinitely. The air chamber is useful in eliminating pulsations and assuring a steady oil pressure to the burners. It is ordinarily supplied with steam systems, and for electric pumps can be made from 4-inch pipe about 14 inches long, capped at one end and the other end connected into the delivery line to the burners by a suitable tee. The gage is important because the oil pressure is a factor in successful operation of the burners, and should be protected by a loop in the pipe connecting it to the oil line. The loop should be filled with cylinder oil or other sulfur-free oil, so that the fuel oil cannot come into contact with the interior mechanism of the gage. The best fuel oil contains sufficient sulfur to injure the best gage in a short time.

It has been found by U. S. Navy tests that for best atomization in oil burners, the viscosity of the oil should be about 8 on the Engler scale, or about 300 Saybolt seconds. The temperature to which oil must be heated to obtain this viscosity depends upon its gravity and type; but for any oil lower than 27 Baumé, this temperature should be greater than room temperature. For an average oil of about 18 Baumé, the temperature required is about 130 deg F. It is, therefore, advisable in most cases to install an oil heater between the pump and the burners. The heater can be one of many standard types and gives little difficulty.

After supplying the required number of burners, the oil feed line should be continued back to the suction line as a circulating line, which should be tapped into the suction line between the tank and the pump. Its chief use is to keep the oil at uniform temperature, independently of the amount of oil burned. A master valve for manual operation or an automatic relief valve can be provided beyond the last burner to assist the relief valve at the pump.

Commercial oil burners are either high pressure, for operation with steam or air from 20 to 100 lbs per square in, or low pressure, for operation with air from 8 to 32 ounces per sq in. High-pressure burners are used with dry steam or air from a compressor; low-pressure burners require a blower. This blower should be of the constant-pressure turbo-blower type; for best results the air pressure should not be lower than 16 ounces, although as low as 8 ounces can be used

The piping from the blower to the burners can be either standard metal pipe or sheet-iron pipe, and should contain slide damper blast gates rather than valves for air regulation, because of their lower friction losses and quicker action. If possible, blast gates should be located about 18 in from the burner to avoid the effect of turbulence from the gate.

The opening in the furnace wall, through which the burner is fired, is a neglected but important factor in the correct operation of the burner. This hole must always flare toward the inside surface of the furnace wall, to

avoid interference with the rapid expansion of the atomized oil and air from the burner. The most rapid expansion possible is to be desired when oil is burned, because the velocity is reduced by the expansion and ignition takes place more easily and quickly. For all low-pressure burners of capacity less than 10 gallons of oil per hour, the burner hole should flare from about $3\frac{1}{2}$ in diameter at the outside of the furnace wall to 7 or 8 in diameter at a point 9 in from the outside. For thicknesses in excess of 9 in it is desirable to span the wall with tile and provide a combustion chamber the same size as the burner block (about 10 in square) from the burner block to the inside of the wall. For burners of more than 10 gallons per hour capacity, the hole should start with a diameter of 5 in and have a corresponding flare. These holes should always be laid with high-temperature cement and made perfectly smooth.

Assuming that the oil equipment and piping have been completed and that the brickwork in the furnace has been arranged according to the above principles, the next consideration is lighting the furnace. This is not as easy as it looks in most cases, and without some knowledge of the fundamental facts of oil-burner operation, the first experience can be decidedly unpleasant.

The chief source of trouble in lighting a cold furnace is the effect of the cold surfaces on combustion. When a mixture of atomized oil and air is ignited and fired into a cold furnace against cold brick and metal surfaces, the temperature of the products of combustion is suddenly reduced, and, as a result, a large percentage of the finely divided carbon particles which have not yet had an opportunity to burn are cooled below the ignition temperature and form dense smoke, or are deposited in the form of soot on the cold surfaces. The difficulty is more pronounced in the case of oil than of gas, because the particles are larger and more difficult to burn rapidly. As the brick surfaces become hotter they offer increasing help in vaporizing the oil.

The recommended procedure for lighting oil burners is as follows (the same rules can apply also to gas burners):

After placing a lighted ball of waste saturated with carbon oil or other lighter close to the mouth of the burner,

(1) Turn on a slight amount of atomizing air or steam, just sufficient for ignition of a slight amount of oil or gas.
(2) Allow a small amount of fuel to enter the furnace, so that a small but steady flame is maintained.
(3) Increase the air and then the fuel a little at a time until the maximum amount of fuel which will burn steadily in the cold furnace is reached. Allow the burner to operate at this point until the surrounding bricks become hot, and then increase the air and fuel as fast as the hot brickwork will sustain ignition.

(4) Adjust the oil to the required amount and increase the air supply until smoking just disappears.

The atomized oil and air leave an oil burner with a velocity greater than the speed of ignition of the mixture when not assisted by the vaporizing effect of hot brick surfaces. For this reason it is always advisable to place a brick or baffle wall in front of an oil burner, at least while lighting, in order to break up the velocity and allow the oil to ignite before passing into the heating chamber of the furnace. This arrangement also tends to confine the greatest heat to the brickwork near the burner, causing it to heat faster and accelerate combustion, as already explained. If it is not possible to arrange a brick in front of the burner, a metal bar can often be substituted and removed after the burner is started.

It should be remembered in starting an oil burner that unburned combustion gases constitute an extremely effective fire extinguisher, so that if too much oil is turned on at first, the furnace will be filled with cold smoke and the flame will be smothered. When this happens, the oil should be shut off and the air or steam allowed to blow the gases out of the furnace before again attempting to light the burners.

The danger of an explosion when lighting oil burners is not as great as with gas fuel, but some risk is present and care must be used. For this reason, never turn on the oil first, because it will collect in the furnace and when sufficient air has been admitted, an explosion may result. Doors should always be open when the furnace is lighted.

Before lighting a green furnace which has just been built, it should be dried out by means of a wood, coal, or gas fire at low temperature. This removes the moisture in the brick and clay and prevents cracking of the brickwork when heated to high temperature. For large furnaces, this process should last for several days, but in all cases should be continued until steam and moisture are no longer given off by the brickwork.

In practically all oil burners, the supply of oil is regulated by a needle valve which can become clogged by dirt in the oil. To reduce this condition to a minimum, the oil pressure at the burner should not exceed 8 to 10 lbs per sq in. With this low pressure the valve will be farther open for a given flow of oil, and larger pieces of dirt will pass without trouble. Many types of oil burners are available, in all of which every effort is made to achieve the maximum atomization with the minimum atomizing pressure, or energy. In some designs attention is also directed to the control of oil-air ratios.

**Burning Solid Fuels.** Fuel in solid form is the most difficult to burn with anything approaching scientific accuracy, principally because in large lumps the air is in only partial contact with the fuel. Bituminous coal contains an average of 13,500 Btu per pound and requires about 130 cu ft of free air for perfect combustion of each pound. With improper firing of

coal, a considerable excess of air is sometimes supplied to insure combustion of the coal. The heating of this excess air to furnace temperature of course reduces the efficiency of the furnace. For example, a loss of 7.3 per cent in the efficiency of a furnace at 2000 deg F is caused by 20 per cent excess air. Losses are also caused by incomplete combustion of the coal because of insufficient air. Incomplete combustion is indicated by smoke and soot and is measured by analysis for carbon monoxide in the flue gases. The presence of 2.0 per cent carbon monoxide in the flue gases with no oxygen present represents a loss of 7.5 per cent of the heat in the fuel.

When coal is burned on the grate to heat batch-type furnaces for forging or rolling, the area of the grate should be at least 25 per cent of the area of the furnace hearth, because if the grate is too small it will be rapidly burned out by an excessive rate of firing. The above grate size will result in a maximum firing rate of about 20 lbs of coal per hour for each square foot of grate surface at maximum furnace production.

Furnace temperatures are particularly important in the combustion of coal. At low furnace temperatures it is very difficult to burn without excessive smoke and soot. The difficulty is frequently solved by the use of bridgewalls which confine the heat of the fire and build up a localized heat in the combustion chamber (or Dutch oven), but this solution frequently runs afoul of the laws governing the distribution of heat in the furnace. To secure a uniform low temperature by suitable baffling in a furnace heated by very hot combustion chambers is a difficult problem for both the combustion engineer and the operator.

The use of stoker-fired coal with controlled forced air is a step in the right direction from the combustion standpoint, because with forced-draft stokers it is possible to regulate a positive furnace pressure as well as to control coal-air ratio. The operation of the stoker may also be governed by a thermocouple in the furnace which gives automatic furnace-temperature control, whereas none of these positive controls of furnace conditions are possible with hand-fired coal. The use of a stoker saves coal as compared with hand-firing, and permits the use of a cheaper size of coal.

As has been previously stated, the use of pulverized coal for metallurgical furnaces is increasing, on the theory that this more abundant fuel should be used in place of fuels of higher form value (fuel oil and gases) wherever possible. After proper drying and pulverizing of the coal, the burner problems involved are comparatively simple. A portion of the air required for combustion is used to convey the coal through the burner (primary air), and the remainder (secondary air) is introduced in one of several ways, each designed to produce the best mixture with the coal particles. Fully automatic control of temperature, coal-air ratio, and furnace pressure has been successfully applied to furnaces fired with pulverized coal.

### Cost of Industrial Fuels

The comparative cost of several common fuels at the burner and in the furnace are shown in Table 23. The cost per million Btu at the burner is the figure most commonly used in selecting fuels, and is sufficiently accurate in most cases. The cost in the furnace is more accurate and is the cost per million Btu after subtracting the loss in sensible heat carried out by the flue gases. The combustion efficiency (100 minus flue gas losses of Table 12) depends upon the furnace temperature, so that cost is also a function of furnace temperature. The table shows combustion efficiency and costs for 1000 and 2000 deg F. This tabulation shows the important effect of large flue gas volumes in increasing the cost in the furnace for producer gases and blast-furnace gas. The difference is possibly offset in part by the greater transfer of heat in the furnace having the greater circulation of a large volume of gas, although data are not available to prove the truth of this contention.

In the future, the trend of fuel technology as applied to industrial heating furnaces will probably be toward application of the cheaper fuels to large heating furnaces for temperatures above 2000 deg F. This will be accomplished by further improvements in the application of these fuels, and with these improvements, some of the ground lost by these fuels in the recent striving for quality of product will be regained as the necessity for economy as well as quality increases.

For furnaces for intermediate temperatures (from about 1800 to 2000 deg F) and for smaller furnaces at high temperatures, fuel oil and coke-oven gas — the latter used directly, as in the steel mills, or mixed with other gases as supplied by the utilities — will probably compete on a straight price basis with the clean gases, such as natural gas, artificial gas, and butane. At still lower temperatures, convection heating is the most logical method of heat transfer and should become a permanent improvement, especially as the liquid fuels and dirty gases can be applied successfully to convection units at a saving in cost.

The use of heat-saving devices has made slow progress in this country, but they may be of increasing interest in the future. Control of atmosphere in regenerative furnaces is made difficult by the nature of their operation, and when economic pressure does demand a saving in fuels, the recuperator and the waste heat boiler will be the two logical devices for this purpose. Recuperators are being constantly improved, both here and abroad, and improved designs will be available, whether of refractory tile, silicon carbide tubes, or heat-resisting alloys.

An idea of the savings possible with recuperation of combustion air can be gained from Table 24, which shows the percentage saving in fuel consumption resulting from preheating combustion air to various temperatures in furnaces fired by natural gas at several different temperatures. The

Table 23. Comparative Cost of Fuels

| Fuel | Net heating value per unit * (Btu) | Assumed cost per unit † | Preparation cost per unit † | Cost at burner per million Btu | Combustion efficiency at 1000 deg F | Combustion efficiency at 2000 deg F | Cost in furnace per million Btu at 1000 deg F | Cost in furnace per million Btu at 2000 deg F |
|---|---|---|---|---|---|---|---|---|
| Anthracite Producer Gas | 150 | $5.00 | $3.40 | $0.42 | 74% | 44% | $0.57 | $0.96 |
| Raw Bituminous Producer Gas | 140 | 2.45 | 1.55 | 0.20 | 73 | 41 | 0.27 | 0.49 |
| Blast Furnace Gas | 90 | 0.01 | | 0.11 | 62 | 25 | 0.18 | 0.44 |
| Coke Oven Gas | 420 | 0.08 | | 0.19 | 79 | 50 | 0.24 | 0.38 |
| Manufactured Gas | 480 | 0.50 | | 1.04 | 79 | 50 | 1.32 | 2.08 |
| Natural Gas | 1,000 | 0.30 | | 0.30 | 78 | 49 | 0.38 | 0.61 |
| Butane | 3,000 | 0.06 | 0.005 | 0.68 | 79 | 50 | 0.86 | 1.36 |
| Fuel Oil | 140,000 | 0.04 | 0.005 | 0.32 | 80 | 52 | 0.40 | 0.61 |
| Tar | 150,000 | 0.04 | 0.007 | 0.31 | 80 | 54 | 0.40 | 0.57 |
| Pitch | 165,000 | 0.025 | 0.007 | 0.19 | 80 | 54 | 0.24 | 0.35 |
| Hand-fired Coal | 14,000 | 5.00 | 1.00 | 0.21 | 80 | 59 | 0.26 | 0.36 |
| Stoker-fired Coal | 14,000 | 3.50 | 1.50 | 0.18 | 80 | 59 | 0.23 | 0.31 |
| Pulverized Coal | 14,000 | 5.00 | 2.75 | 0.28 | 80 | 59 | 0.35 | 0.48 |

* Units are cu ft for gases; gallons for oil, tar, and pitch; lbs for coal.

† Units are tons for coal and producer gases (70% conversion efficiency for bituminous and 80% efficiency for anthracite); 1000 cu ft for other gases; and gallons for butane (as delivered), fuel oil, tar, and pitch.

savings vary for lean and rich fuels, because lean fuels produce a relatively greater amount of flue gases and require a greater amount of combustion air per unit of heat released.

In conclusion, the statement is emphasized that to select the proper fuel for industrial heating furnaces intelligently, it is essential to understand the chemical and metallurgical requirements, as well as the cost of the heat. A small percentage of rejected steel in its semi-finished state will frequently more than offset the difference in the cost of the fuels under consideration. At the same time, by engineering based upon the latest developments in control, the cheaper fuels can often be applied successfully to the requirements.

Table 24. Approximate Savings in Per Cent, of Natural Gas Which Are Possible by Preheating of Combustion Air

| | Temperature of air preheat (deg F) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 |
| Furnace Temperature | | | | | | | | |
| 1200 deg F | 2 | 7 | 12 | 16 | | | | |
| 1800 deg F | 4 | 10 | 15 | 20 | 24 | 28 | | |
| 2400 deg F | 5 | 13 | 19 | 26 | 31 | 35 | 40 | 43 |

# Chapter 3

## Temperature Distribution and Furnace Control

The distribution of gases and of temperature in a furnace are primarily problems of furnace design, while control of the atmosphere and of the temperature involve the selection of proper instruments, based upon a knowledge of the principles on which these instruments operate.

The development of control instruments has made great strides in the past ten years, and a considerable discussion of these instruments will be of value. The development has followed the increasing necessity for improved quality in steel products of all classes; this quality cannot be obtained unless careful control of heating is provided. As will be shown in

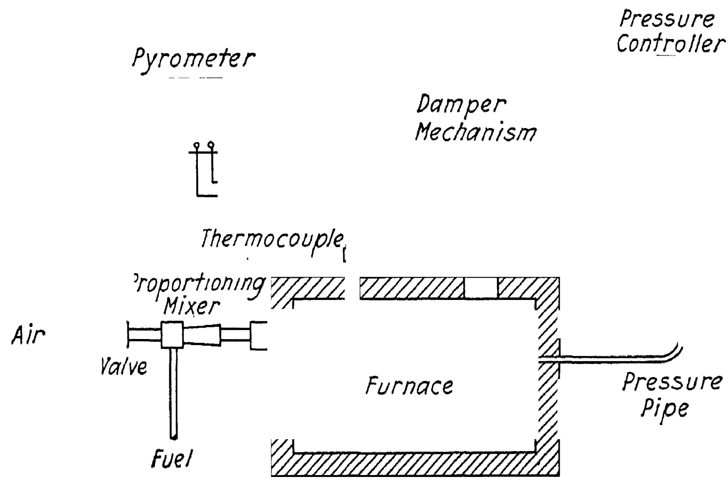



Figure 25. Diagram of furnace controls.

a later chapter, all kinds of steel products receive a number of different heat applications in the course of their manufacture, and great damage may be done in any of these treatments by improperly controlled furnaces.

The subject of furnace control is graphically illustrated in Figure 25, which shows a furnace chamber provided with the three important types of control, *i.e.*, temperature, atmosphere (fuel-air ratio), and furnace pressure.

### Distribution of Temperature and of Gases

As already stated, the distribution of heat in fuel-fired furnaces is principally a matter of design, starting with the method of heat application

and ending with the location and design of combustion chambers and the application of burners. The methods of heat application include:

(1) *Direct firing*, in which the burners fire directly into the heating chamber. This method is commonly used in furnaces over 1900 deg F for all fuels, and for gaseous fuels at lower temperatures when temperature and atmosphere control are not extremely important. There are no separate combustion chambers with this design.

(2) *Overfiring*, in which combustion gases pass through a perforated arch between the heating chamber and the combustion chamber which is located above the heating chamber. This method is frequently used for oil-fired furnaces below 1600 deg F, especially where the conveying method interferes with the underfired method.

(3) *Sidefiring*, in which a bridgewall separates the heating chamber from a combustion chamber on one or both sides of the heating chamber. This method is frequently used for temperatures between 1600 and 2000 deg F where control of atmosphere and prevention of direct flame impingement on the steel are important.

(4) *Underfiring*, in which the combustion chambers are located below the heating chamber. This is the most accurate method available in burner-fired designs for temperatures between 1000 and 1800 deg F.

(5) *Recirculation*, in which large volumes of hot gases are circulated through a duct system which includes the furnace heating chamber and a combustion chamber, which may or may not be separate from the furnace proper. This is the most accurate method of heating for low temperatures under about 1300 deg F and particularly under 1000 deg F, where transfer of heat by convection becomes important. The introduction and discharge of the volume of gases may be at the top, sides, or bottom of the heating chamber, depending upon principles which are very similar to those governing the location of combustion chambers in indirect-fired furnaces. In car-type furnaces under ten feet in width the gases may enter from one side of the furnace and leave through the opposite side. In high vertical furnaces for heat-treating guns or other cylindrical objects, the gases usually enter at the top and leave through the bottom of the furnace. In continuous furnaces, the gases frequently enter at the top and leave at the bottom, with the distribution arranged in zones through the length of the furnace, or, where the height of the furnace is small, the entrance may be at the bottom and the discharge at the top. In still another arrangement for batch furnaces which are limited in depth, the gases may enter at the rear and leave at the front of the furnace. An insulated fan built of alloy metal capable of withstanding high temperature is used to circulate the heating gases, which consist of the products of combustion of the fuel burned in the combustion chamber mixed with

air drawn from the atmosphere. Some idea of the effectiveness of heat transfer at low temperatures with this arrangement may be gained from the fact that for each million Btu of heat input per hour an average of 12,000 cu ft of gases are circulated per minute, while in the usual combustion furnace without recirculation the gases produced and circulated for the same heat input are only about 200 cu ft per minute. In low-temperature furnaces where convection is active, the effect of this greatly increased velocity of gases is to increase production as well as to guarantee temperature uniformity. This type of furnace is described further in Chapter 4. A variation from the recirculating system with separate combustion chamber consists of impeller fan blades suspended on shafts through the furnace roof. These alloy impellers are designed for high volumes against very little static pressure, and are used in both electric and fuel-fired furnaces. In the latter application, sheet alloy baffles are frequently used to shield the fan from the burner flames firing through the sidewalls of the furnace and to direct the circulating gases.

In connection with the design of industrial heating furnaces, the question of combustion chambers for indirect firing is one on which there are many conflicting opinions. These appear to arise from a misunderstanding of the factors which affect the allowable rate of heat liberation in combustion chambers. There have been a number of investigations of the problem of the rate at which heat may be liberated in combustion chambers, usually from the standpoint of the maximum rates which may be attained with different types of premix burners, but these findings are usually impractically high and must be combined with a consideration of the temperature uniformity required within metallurgical furnaces.

The purpose of the following discussion is to develop data from which limitations may be applied by the furnace designer to maximum firing rates which have been reported by investigators who have concentrated only on the factors which affect the speed of combustion.

The best method of studying this problem is to select a specific example for which actual data are available, with which to check the results of calculation. Figure 26 illustrates the section of such an example, which shows a series of combustion chambers in an underfired furnace operating at 1400 deg F in the heating chamber. In this case, the actual fuel burned in each chamber is 130 cu ft of natural gas per hour. The volume of each chamber is 7.5 cu ft, so that the average rate of heat liberation in the chamber is 4.7 Btu per cu ft per second. In such a furnace it is desirable from a temperature uniformity standpoint that the temperature in the combustion chamber be as low as possible to avoid spotty heating of the material in the heating chamber, and a temperature of 2000 deg F might well be specified as a maximum allowable combustion-chamber temperature.

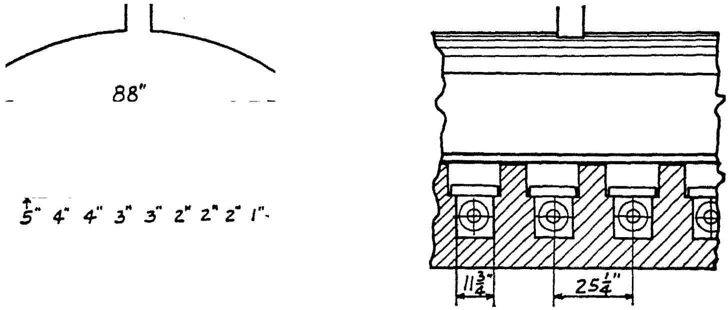



Figure 26. Typical combustion chamber.

To reduce to practice the design of such a chamber, it is necessary to consider all the factors involved, which are included in the simple formula:

$$H = R + G + C$$

where $H$ = Heat liberated in Btu per hour.
$R$ = Heat radiated through slots between baffles or through openings between combustion chamber and heating chamber, in Btu per hour.
$G$ = Sensible heat in the gases leaving the combustion chamber through these openings, in Btu per hour.
$C$ = Heat conducted through the walls and bottom of the combustion chamber, in Btu per hour.

The calculation of each separate factor depends upon the combustion-chamber temperature, and we shall assume that in this case the temperature is 2000 deg F. In this case the value for blackbody radiation at 2000 deg F is 425 Btu per sq in per hour * and at 1400 deg F it is 145 Btu. The total slot area is 300 sq in and the Keller factor for the slot dimensions in this case is 0.62. The total radiation is therefore

$$0.62 \times 300 \times (425 - 145) = 52{,}000 \text{ Btu per hour}$$

The sensible heat in the gases from the combustion of 130 cu ft of natural gas per hour is

$$130 \times 0.82 \text{ lb products/cu ft gas} \times 0.27 \text{ specific heat} \times 2000 \text{ deg F} = 58{,}800 \text{ Btu per hour}$$

The heat conducted through the walls is determined from the area of the ends and bottom of the chamber in this case, and the heat losses depend upon the brick construction of these parts. The heat loss through the bottom shown in Figure 26 is about 475 Btu per sq ft per hour and through the ends about 955 Btu per sq ft per hour (Table 13). The common walls between the chambers, of course, do not lose any heat. For this chamber at 2000 deg F, the conducted heat is about 11,300 Btu per hour.

* The radiation through the openings can be calculated by the method developed by J. D. Keller and described in the author's previous book. (See also Table 12 for values.)

To find the combustion-chamber temperature for any given chamber with given heat input rate, it is necessary to calculate the separate losses for several combustion-chamber temperatures and to plot a curve showing the total losses for different temperatures. The point at which this curve of total losses equals the heat input fixes the combustion-chamber temperature. For this case, Figure 27 illustrates the procedure and shows that for 130 cu ft of natural gas per hour of 920 Btu net thermal value per cu ft, the temperature in the combustion chamber of Figure 26 is 1980 deg F (solid lines in Figure 27) when the heating-chamber temperature is 1400 deg F.

**Effect of Combustion-Chamber Size.** The volume of the combustion chamber is fixed by its length, width, and height. The length is determined in most cases by the width of the furnace, and little variation is possible. Likewise, the width of the chamber is fixed by the burner spacing which is generally between 18 and 30 in. The height of the chamber is the only variable in most cases. Of the various heat losses, a variation in the height changes only the end radiation, which is a small percentage of the total losses.

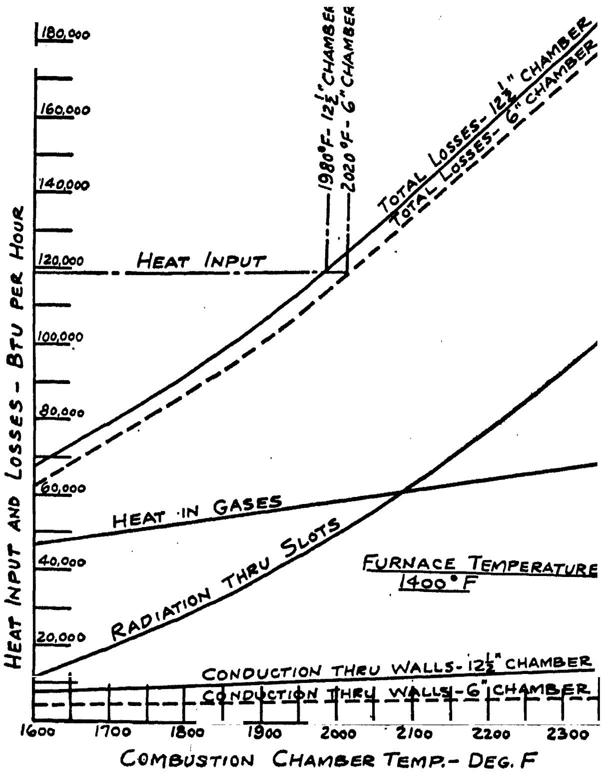
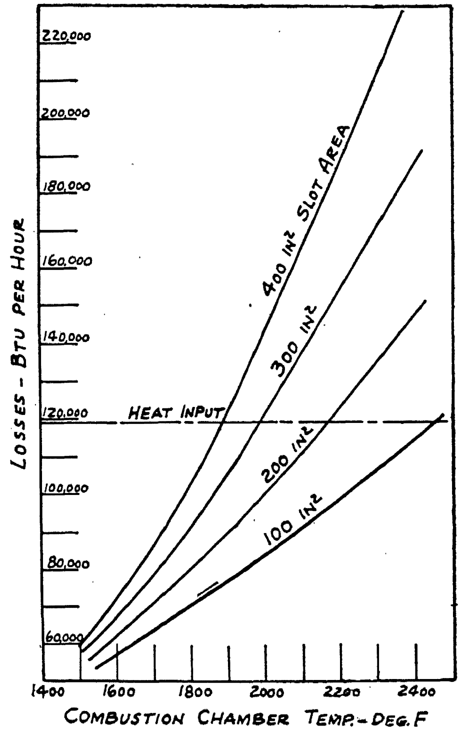



Figure 27. Temperature in chamber for known fuel rate.

The dotted curves of Figure 27 have been prepared from calculations in which all conditions were the same as for the solid lines, except for a chamber height of only 6 in, and it will be seen that the combustion-chamber temperature is 2020 deg F as compared to 1980 deg F for the $12\frac{1}{2}$ in in the first calculation. Actually, a chamber 6 in high for a length of 88 in would result in poor distribution of temperature in the combustion chamber, which is discussed further on. Specifically it may be stated that combustion-chamber height has little effect on the temperature, and can be determined from the standpoint of temperature distribution alone.




**Effect of Port Area.** The effect of ports or other openings between the combustion chamber and the heating chamber is of much greater importance than the volume of the chamber. The total area of these openings affects the combustion-chamber temperature, and the distribution of this total area in the form of ports of various sizes influences the uniformity of temperature in the chamber.

To determine the effect of total area of openings, the total heat losses for various combustion-chamber temperatures have been calculated by the methods outlined above for several total areas of slots, with the chamber $12\frac{1}{2}$ in high in all cases. The result of these calculations is shown by the

curves of Figure 28. The curve for 300 sq in is the same as that of Figure 27. The intersection of each of these curves with the horizontal line representing a heat input corresponding to 130 cu ft of natural gas per hour again gives a combustion-chamber temperature for that input in each case.

From the information of Figure 28 the curve of Figure 29 has been prepared, where the combustion-chamber temperature for each slot area, found graphically from Figure 28, has been plotted against the constant Btu input divided by the port area in sq in in each case.

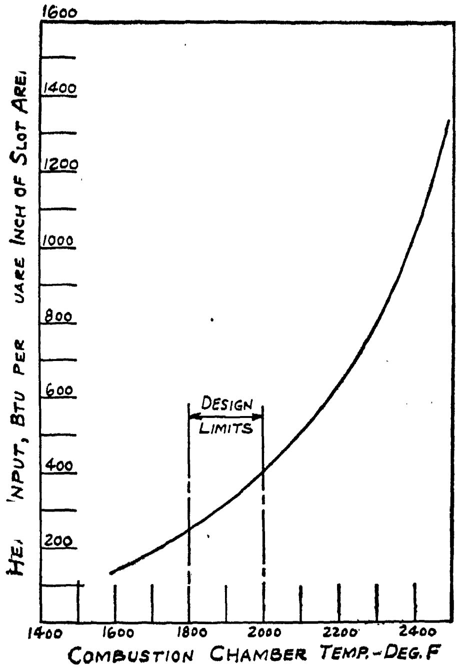



Figure 29. Effect of port area on temperature in chamber.

The logical limits for design in determining the port area for 1400 deg F furnace temperature in the design of Figure 26 are indicated in Figure 29, from which it appears that the design of Figure 26 (400 Btu input per sq in port area) lies at the upper limit of port area. The lower limit is the area at which control of gas distribution to the ports is lost, because the total area is too large to maintain pressure in the combustion chamber with the given gas input.

**Effect of Heat Input.** The effect of heat input in a chamber of given size and given port area can also be illustrated graphically, as shown in Figure 30. This illustration was prepared by calculating the total heat losses at different assumed temperatures in the chamber of Figure 26 for different rates of gas flow and heat input. The combustion chamber tem-

perature was again located by the intersection of each curve with the corresponding rate of input.

From this information, the chamber temperature has been plotted against the rate of liberation found by dividing Btu rate by combustion-chamber volume, and the result is the solid line of Figure 30. The dotted line is a similar curve for all the same conditions except a total slot area of 400 instead of 300 sq in.

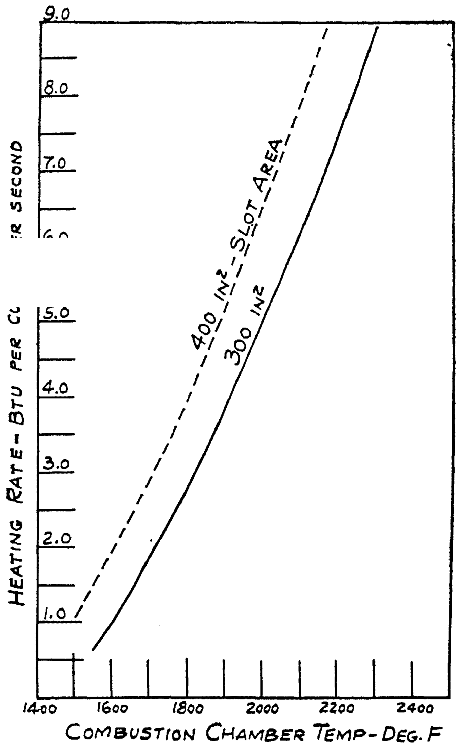



Figure 30. Effect of heating rate and ports on chamber temperature.

A summary of the conclusions from this study is:

(1) The losses from a combustion chamber are the total of the losses from sensible heat in the gases, wall conduction, and radiation through openings.
(2) All of these losses depend upon the combustion-chamber temperature.
(3) The combustion chamber reaches the temperature at which the total of the losses exactly equals the heat input rate.
(4) The heat losses to the walls are of minor importance.
(5) The length and width of most chambers is fixed by other considerations.
(6) The height has little effect on combustion-chamber temperature, and is determined from consideration of temperature uniformity.

(7) The area of openings is of major importance in fixing chamber temperature.
(8) The Btu per hour liberation of heat in the chamber of Figure 26 should not exceed 400 Btu per sq in of port area.
(9) The rate of heat liberation in combustion chambers should not exceed 7 to 10 Btu per cu ft of volume per second in most chambers for industrial furnaces.

The next question of importance in the design of combustion chambers is that of temperature uniformity in the heating chamber itself. In the preceding discussion, involving heat liberation only, it was found that the combustion-chamber height which satisfied the heat liberation requirements could be too low for proper uniformity of temperature. A good rule to follow in this connection is to set the height at a minimum of $7\frac{1}{2}$ in for chambers less than 48 in long and at a minimum of $12\frac{1}{2}$ in for chambers exceeding 48 in in length. An extra $2\frac{1}{2}$ in in all cases is desirable if space is available.

Temperature is an important consideration in temperature uniformity of indirect-fired furnaces, because at lower furnace temperatures the difference between the combustion-chamber temperature and the heating-chamber temperature is increased, which increases the necessity for careful arrangement of the ports. At the upper limit for indirect-fired furnaces (about 1800 deg F) the temperature difference is only 200 deg F if the design has been based upon a maximum temperature of 2000 deg F in the combustion chamber, and the possibilities for uneven heating are reduced. Very uniform temperatures are possible in furnaces of this type at low temperatures (below 1000 deg F), but the modern convection furnaces with rapid circulation accomplish the result more easily and with greater economy.

A very important consideration is the burner setting, particularly where the chamber is fired from one end only. The burner block should be set flush with the inside of the wall to reduce the size of the hot port, which is not balanced by a similar hot area at the other end. When the block is recessed into the wall the entire area of the block becomes very hot and radiates heat to the burner end of the chamber. Since there is no similar radiating area at the opposite end, uniformity of the chamber is difficult to accomplish, even with adjustment of the ports.

The most important factor affecting the temperature distribution to the furnace is the arrangement of the ports between the combustion chamber and the heating chamber. As was previously explained, the total area of the ports must be small enough to maintain a small distributing pressure in the combustion chamber and large enough to liberate sufficient heat by radiation that, with the help of other losses, the temperature will be maintained under 2000 deg F at the necessary heat input rate.

The ports must ordinarily be balanced to offset the effect of flame velocity from the burner. At all lengths up to about 8 feet, the tendency will be for the chamber to reach maximum temperature at the end opposite the burner because of the velocity from the burner. To offset this effect, the ports must usually be graduated in size from one end to the other, with the largest areas at the burner end. An idea of this practice may be gained from the following examples.

Since the velocity is an important factor in distributing the ports, the distribution will vary with the amount of fuel burned, and to some extent with the kind of fuel. No exact calculation has been devised to determine the arrangement for all conditions, and the best plan is to arrange the construction so that the ports may be easily adjusted by shifting spacer tile or by other means.

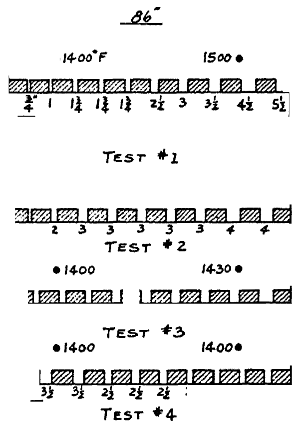



Figure 31. Combustion chamber arrangement in which the spaces between tile were shifted and the results measured by thermocouples as shown in the heating chamber above the ports.

Figure 31 illustrates a combustion-chamber arrangement in which the spaces between tiles were shifted and the results measured by thermocouples, as shown in the heating chamber above the ports. The furnace was at about 1400 deg F in the heating chamber and the heat input to each combustion chamber was constant at 110,000 Btu per hour. The adjustment of ports necessary to offset the velocity from the gas burner at one end is illustrated by these results.

In the first part of the diagram the openings are largest at the end opposite the burner and the furnace temperature is 100 degrees hotter at that side than it is at the burner side. Graduation of the openings in the second test reduced the variation to 60 degrees, and further graduation in the third test reduced the variation to 30 degrees. In the fourth test, the openings are largest at the burner end, and the heating chamber has become uniform.

Figure 32 shows the arrangement of ports in a furnace 67½ in wide with a temperature of 1600 deg F in the heating chamber and an average heat input of 60,000 Btu per hour through the burner at one end of the combus-

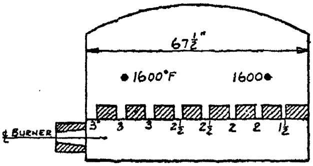



Figure 32. Arrangement of ports in a furnace 67½ inches wide, with a temperature of 1600 deg F in heating chamber and heat input of 60,000 Btu through burner at one end.

tion chamber, which is 10 inches wide in this furnace. The Btu input in this case is therefore $\frac{60{,}000}{19.5 \text{ in of ports} \times 10}$, or 308 Btu per hour per sq in of port.

Figure 33 illustrates the difference in port distribution required in furnaces of the same width but operating uniformly at high and low temperatures. In each case the heating chamber width is 54 in, and the heat is supplied by a burner at one end of the combustion chamber. For each chamber supplying heat to the heating chamber at 1600 deg F, the width is 11 in and heat input is 80,000 Btu per hour, or 440 Btu per hour per sq in of port, and the effect of velocity is seen in the port arrangement.

In the low-temperature chamber operating at 925 deg F the heat input to the combustion chamber is 40,000 Btu per hour, which is 300 Btu per hour per sq in of port in this case. The rate of heat liberation per cu ft

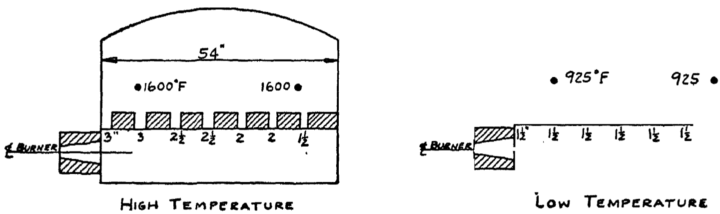



Figure 33. Illustrating the difference in port distribution required in furnaces of the same width but operating at different temperatures.

of volume is only 2.5 Btu per cu ft per second. With this low burner capacity the velocity through the chamber is small and it was not necessary to offset this low velocity by unequal port distribution to achieve uniformity of temperature in the heating chamber.

Figure 34 shows an overfired furnace with a chamber 31 in wide, in which the heat liberation was 1100 Btu per hour per sq in of port, which caused the combustion chamber to operate at a temperature of 2400 deg F for a heating chamber temperature of 1600 degrees. As has been stated, this rate of liberation should be below 400 Btu per hour per sq in of port in most furnaces. In such narrow chambers of either overfired or under-

fired design, the ports may be uniformly distributed without affecting the uniformity in the heating chamber, because there can be very little variation of temperature in such short combustion chambers.

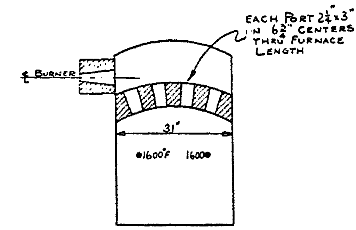



Figure 34. Overfired furnace in which combustion chamber had to operate at 2400 deg F for a heating chamber temperature of 1600 deg F, due to size of ports.

From numerous tests on furnaces of different dimensions and operating at different temperatures, reasonably close approximations for port distribution in furnaces of various designs have been obtained; these are represented graphically in Figure 35. The use of figures derived from this chart will give approximately uniform distribution of temperature in the heating chamber of indirect-fired furnaces. With proper design the distribution of ports can then be adjusted with no more than one change to perfect conditions. Without good original approximation, a large number of adjustments is often required. In the preparation of Figure 35 it was assumed

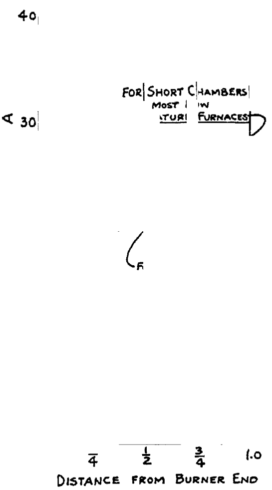



Figure 35. Graphical summary of numerous tests on furnaces of different dimensions and operating at different temperatures, giving approximations for port distribution in furnaces of various designs.

that the burner blocks are set flush with the inside of the wall to avoid unbalanced radiation, and that the combustion chambers in the furnace are on centers of about 18 to 24 in. This latter assumption fixes the rate of heat release in the chamber at a value under 10 Btu per cu ft of volume per second.

Additional conclusions pertaining to the design of combustion chambers may be summarized as follows:

(1) Combustion chambers should be at least $7\frac{1}{2}$ in high when under 48 in long, and at least $12\frac{1}{2}$ in high when over 48 in.
(2) Burner blocks must be set flush with the inside of the furnace brickwork, to avoid unbalanced radiation at the two ends of the chamber.
(3) The distribution of ports between the combustion chamber and the heating chamber must be correctly arranged to offset the effect of flame velocity from the burner.
(4) Distribution of ports is in general more uniform in narrow furnaces and in furnaces operating at low temperature.
(5) Furnace design should be such as to permit changing the distribution of ports with a minimum of difficulty.
(6) No exact rules for port distribution can be formulated, but it is possible to set the ports with reasonable accuracy, so that very little subsequent adjustment is required.

A complete series of tests of the uniformity prevailing in the heating chamber of similar furnaces when fired by different methods was made by the author, and the results are of interest in this discussion. The test furnace for these experiments was 60 in deep by 72 in wide inside, *i.e.*, the dimensions of the chamber for the direct and underfired arrangements. The bridgewall reduced the inside width for sidefiring to about 43 in. The height in all cases was 32 in from the floor to the skewline of the arch.

Six thermocouples were projected through the rear wall, three just above hearth level and three at the level of the skewline of the arch. In all tests the furnace was held, or "soaked" at temperature for at least 8 hours before the readings were taken.

The numerical values of the maximum variation in temperature between the points of highest and lowest temperature for each test are shown in Figure 36, which brings out the closer control obtainable with the sidefired design as compared to the direct-fired, and also shows the accuracy possible with the underfired arrangement. The values given for the underfired furnace are for the worst conditions, and can be improved to almost perfect uniformity by simple adjustment of the ports across the width of the hearth, as has just been discussed. The comparisons of the illustration are for empty furnace chambers in all cases.

Figure 36 indicates the effect of temperature in the furnace upon the uniformity of temperature in the heating chamber for different methods of firing the test furnace. Tests in many commercial furnaces have shown that these curves are a reliable guide to the comparative temperature control possible with these furnace arrangements. At higher temperatures closer control is possible than at lower temperatures, because as the furnace

temperature increases the ratio of heat transferred by radiation to that transferred by convection increases, and the uniformity is less dependent upon even circulation of the gases to all parts of the chamber. At 900 deg F about 20 per cent of the heat is transferred by convection, and the gases

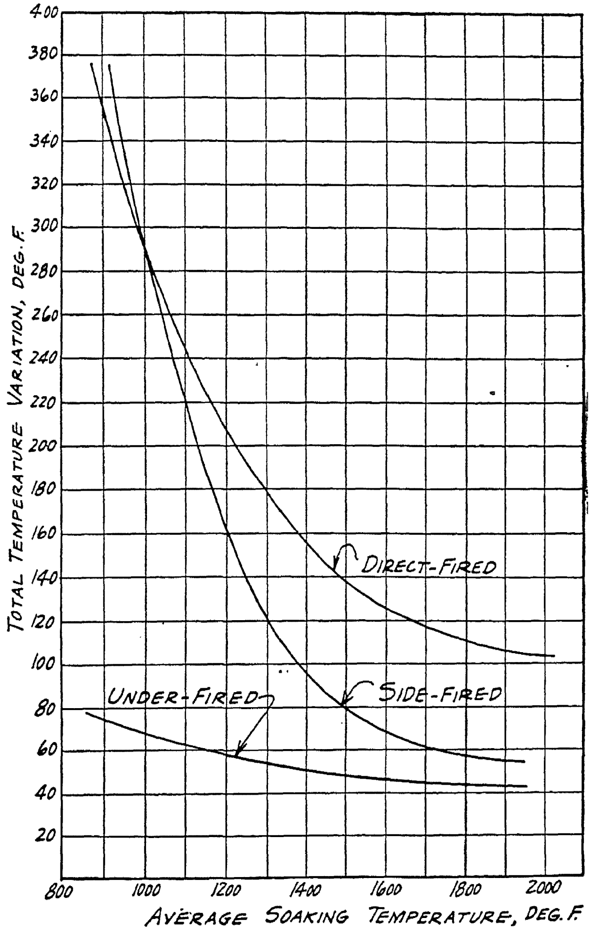



Figure 36. Effect of temperature on temperature uniformity (empty furnace).

must circulate very uniformly to obtain good temperature control. At 1600 deg F the proportion of heat transferred by convection drops to about 10 per cent, and heat is actively radiated to all parts of the furnace.

This discussion has been confined to the state existing under "soaking" conditions, but the progressive uniformity from the time the furnace is lighted is of interest. Figure 37 shows a curve for uniformity of temperature plotted against time, from a typical test for each method of firing. This

illustration shows how the hot flame of the direct-fired furnace produces a fast initial heating of the entire chamber, with a relatively low temperature difference from the start. With sidefiring the temperature of the gases coming over the bridgewall is lower and at less velocity, and the refractories

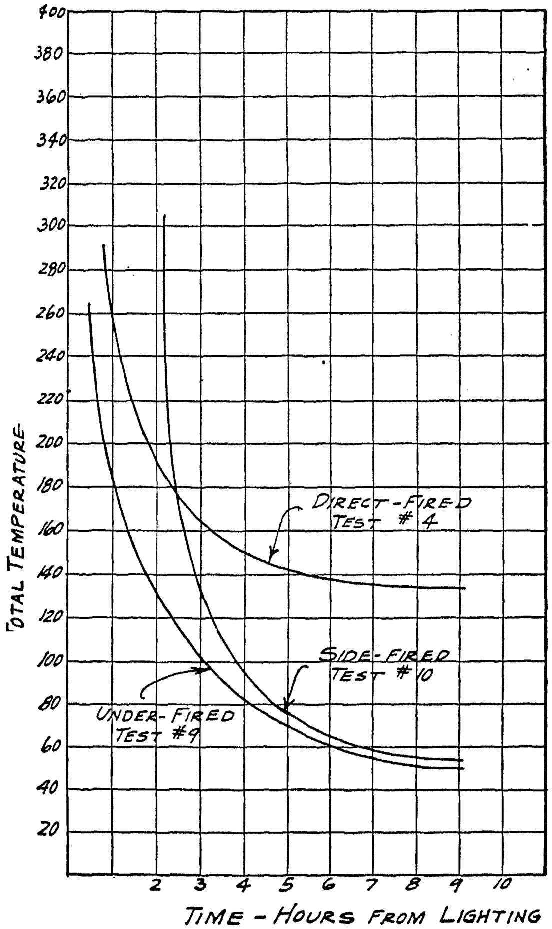



Figure 37. Effect of time on temperature variation (empty furnace).

are heated more slowly, starting at the top and gradually working down to the bottom with high initial temperature variation. As the furnace nears final temperature it approaches the temperature of the gases and better uniformity results than with direct firing. Underfired furnaces heat up very uniformly from the start because the hot gases are distributed uniformly and wipe all sections of the refractory lining evenly.

Variations in furnace width can be taken care of by firing from one or

both sides of a furnace, and for any method of firing the horizontal variation will usually not be as great as the variation caused by the height of the furnace. The horizontal variation in a furnace of any width should be controllable to within 50 deg F across the width for any method of firing. Vertical control of temperature within 75 deg F maximum variation for sidefiring and 150 deg F for direct-firing (flame temperatures) is obtainable with burners or bridgewall located up to 5 feet above the hearth and furnace temperatures of 1600 deg F and greater. For underfiring, the variation will be less. These values are based upon an empty furnace for "soaking" conditions, and will be slightly reduced when the charge is properly placed in the furnace.

The effect of heating material is to improve the uniformity of "soaking" temperatures in furnaces, because disrupting the circulation of gases gives better distribution to all parts of the furnace. Also, the area of radiating surfaces is greatly increased; this causes a multitude of reflections of radiation to distribute the heat to all parts of the furnace. It is essential that the heating material be properly located to allow free circulation of gases if maximum uniformity of temperature is to be obtained. It is desirable in all cases to elevate the charge so that circulation underneath will heat the furnace bottom, which in turn will radiate to the bottom of the charge.

In conclusion, the data given indicate that underfired, sidefired, and direct-fired furnaces, in the order named, are decreasingly controllable in temperature uniformity. The selection of a method of firing is primarily dependent upon the method of material handling in the furnace and the temperature desired; but where there is a free choice between methods, information on the characteristics of the different methods is of value.

## The Control of Temperature

The development of commercial instruments for measuring and controlling temperatures in industrial processes has been so rapid that even the industrial furnace engineer becomes confused and loses track of the principles underlying the operation of the different instruments and methods which are identified by so many trade names. The purpose of this discussion is to classify the apparatus available for this purpose and to describe briefly the operation of the principal instruments available in each class.

The apparatus for temperature measurement and control may be classified as follows:

- (A) Temperature measuring instruments
  - (1) Thermoelectric pyrometers
    - (a) Potentiometer
    - (b) Millivoltmeter
  - (2) Optical pyrometers
  - (3) Radiation pyrometers

Additional conclusions pertaining to the design of combustion chambers may be summarized as follows:

(1) Combustion chambers should be at least $7\frac{1}{2}$ in high when under 48 in long, and at least $12\frac{1}{2}$ in high when over 48 in.
(2) Burner blocks must be set flush with the inside of the furnace brickwork, to avoid unbalanced radiation at the two ends of the chamber.
(3) The distribution of ports between the combustion chamber and the heating chamber must be correctly arranged to offset the effect of flame velocity from the burner.
(4) Distribution of ports is in general more uniform in narrow furnaces and in furnaces operating at low temperature.
(5) Furnace design should be such as to permit changing the distribution of ports with a minimum of difficulty.
(6) No exact rules for port distribution can be formulated, but it is possible to set the ports with reasonable accuracy, so that very little subsequent adjustment is required.

A complete series of tests of the uniformity prevailing in the heating chamber of similar furnaces when fired by different methods was made by the author, and the results are of interest in this discussion. The test furnace for these experiments was 60 in deep by 72 in wide inside, *i.e.*, the dimensions of the chamber for the direct and underfired arrangements. The bridgewall reduced the inside width for sidefiring to about 43 in. The height in all cases was 32 in from the floor to the skewline of the arch.

Six thermocouples were projected through the rear wall, three just above hearth level and three at the level of the skewline of the arch. In all tests the furnace was held, or "soaked" at temperature for at least 8 hours before the readings were taken.

The numerical values of the maximum variation in temperature between the points of highest and lowest temperature for each test are shown in Figure 36, which brings out the closer control obtainable with the sidefired design as compared to the direct-fired, and also shows the accuracy possible with the underfired arrangement. The values given for the underfired furnace are for the worst conditions, and can be improved to almost perfect uniformity by simple adjustment of the ports across the width of the hearth, as has just been discussed. The comparisons of the illustration are for empty furnace chambers in all cases.

Figure 36 indicates the effect of temperature in the furnace upon the uniformity of temperature in the heating chamber for different methods of firing the test furnace. Tests in many commercial furnaces have shown that these curves are a reliable guide to the comparative temperature control possible with these furnace arrangements. At higher temperatures closer control is possible than at lower temperatures, because as the furnace

in the case of recording instruments. The galvanometer is of the
type with practically no mechanical friction, and the mechanis
continuously by a small synchronous motor. This mechanism is
strip chart and round chart recorders and controllers as well as in non-recording controllers.

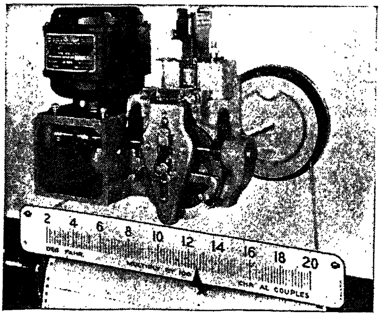



Figure 38. Mechanism of potentiometer type pyrometer.

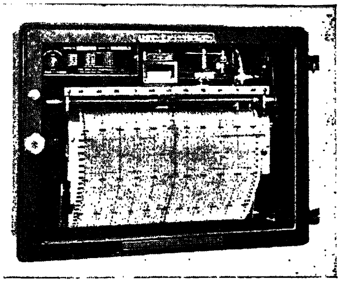


Figure 39. Recording potentiometer pyrometer.

Figure 39 illustrates a similar instrument employing the same principles but differing in details of design. All these instruments can be furnished to indicate or record multiple points, in which case the pyrometer successively connects to the circuit of each thermocouple in turn and records its value. The readings are distinguished by printing different numbers on the record or by utilizing ink of different colors. Figure 40 shows a

Figure 40. Portable potentiometer pyrometer.

portable instrument which employs all the same principles and important parts, but is simplified by absence of automatic features and drive mechanism.

A very interesting new development employs a beam of light in balancing the galvanometer. This inertia-less beam of light is reflected by a mirror

galvanometer on a phototube, current from which is amplified to operate a relay. Shutters intermittently raised in front of the tube detect deflection of the light beam, and synchronized electric contacts control the motion of a contact carriage across the chart and slide wire.

Much the same principles are used in a high-speed recorder, capable of following variations of temperature such as that of a rail as it passes through

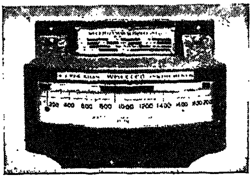


Figure 41. High-resistance indicating pyrometer of the multivoltmeter type.

a rolling mill. The speed of this instrument is such that the pen can move across the full scale of the chart and record a balance point in not more than two seconds.

In the millivoltmeter type of pyrometer the small voltage from the thermocouple is not balanced out, but is measured directly by a very sensitive galvanometer, calibrated in degrees of temperature. These instruments are usually built with high internal electrical resistance to minimize the effect of change in resistance of the thermocouple circuit.

A typical example of this type of instrument is illustrated in Figure 41, which is a high-resistance indicator only in this case, and includes automatic compensation for cold-junction temperature, a 9-in chart, and a dust-proof case. Figure 42 shows one of several instruments used for checking purposes and for immersion in liquid metals, where the thermocouple is attached directly to the galvanometer to form one complete instrument.

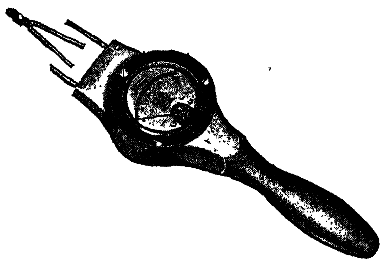


Figure 42. Immersion pyrometer.

In low-resistance pyrometers of this type, an accuracy of 2 per cent is claimed for a maximum length of five feet from the thermocouple to the pyrometer and with a thermocouple made of wire of heavy gage. The advantage of low resistance in such pyrometers is an increase in the ruggedness of the design.

**Optical Pyrometers.** In this type of pyrometer, the light from the hot body is focused in the instrument and compared with the light from a

standard calibrated electric lamp. The light from the wire filament of this lamp is balanced against the brightness of the furnace or hot object to obtain the temperature reading. The balance usually is obtained by visual inspection through the eyepiece of the instrument, and by varying the resistance in the circuit of the standard filament or the light from the hot body the two colors are made to appear identical.

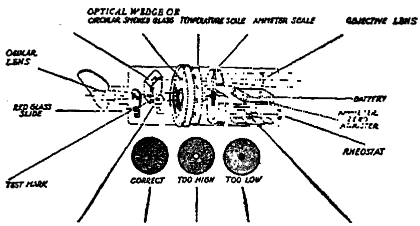



Figure 43. Principle of operation of one optical pyrometer.

Figure 43 shows the unique principle employed in one make of pyrometer which makes possible extremely rapid temperature determination of minute spots or fast-moving objects. The matching of brightness in this pyrometer is effected by making the apparent brightness of the glowing body equal to a light of constant current intensity (as furnished by the pyrometer) by passing the light emitted from the body through a prism and circular optical wedge of varying density. This is done by rotating the graduated optical absorption wedge to change the brightness of the hot body until a small luminous test mark in the field of vision disappears. The temperature corresponding to the position of the rotated absorption wedge can be read directly from a wide scale attached to the wedge. The instrument is equipped with an ammeter and a rheostat in order to standardize the current passing through the filament. The pyrometer is totally self-contained and weighs only three pounds.

Another manufacturer varies the filament intensity of the standard lamp to match the brightness of the glowing body, as in Figure 44, by varying the filament current, which is read and converted to temperature by reference to a calibration chart.

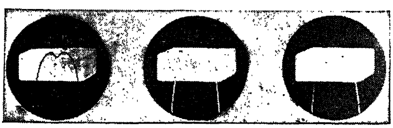


Figure 44. Principle of operation of one optical pyrometer.

Another instrument has a direct scale reading, and is of the type in which the brightness of the standard lamp is varied to match the brightness of the image of the object whose temperature is to be measured. The temperature is read directly from the scale of a calibrated milliammeter,

and correction for deviation from "black body"* can be applied, if desired, from a correction chart.

An interesting development is the optimatic system for indicating or recording temperatures of bodies in motion or at rest by the optical pyrometer method, but without the aid of the human eye (Figures 45 and 46). This system employs photoelectric tubes, the electrical resistance of which varies with the intensity of light to which the tube is exposed. Two photo-

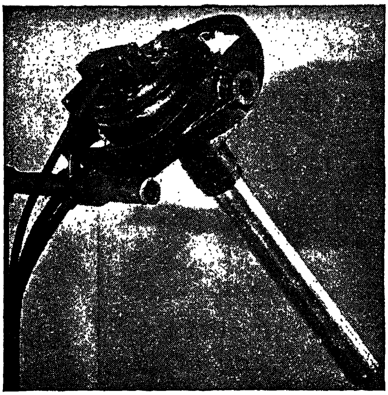


Figure 45. Automatic optical pyrometer for high-speed operation.

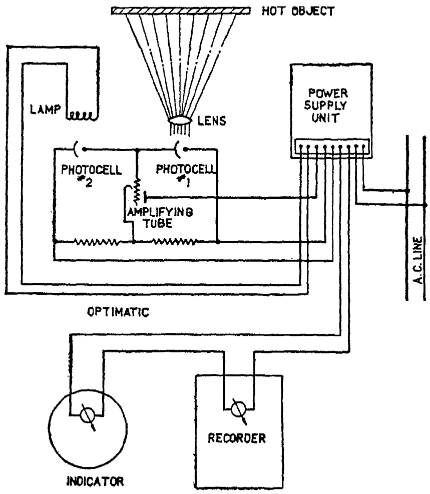



Figure 46. Schematic diagram illustrating principle of operation of optimatic optical pyrometer.

cells in a bridge circuit are used, one exposed to the hot object and the other to the light from a balancing lamp. As the brightness of the hot object varies, the resistance of the first photocell varies and changes the current in an amplifying tube, which in turn changes the current to the standard lamp to bring its light and the second cell into equilibrium with the first tube. The galvanometer in the lamp circuit is calibrated in degrees of temperature.

**Radiation Pyrometers.** The operation of this type of pyrometer is based upon the principle of measurement of total radiant energy (*i.e.*, both heat and light waves) emitted by a hot body whose temperature is to be ascertained. The theoretical relation between the temperature and the radiant energy emitted by it is given by the well-known Stefan-Boltzman

* A "black body" is one which absorbs all and does not reflect or transmit any of the radiation falling upon it. This condition is closely approximated by a pyrometer sighted through a small opening into the interior of a furnace or upon an object surrounded by a hot furnace; correction is necessary when measuring the temperature of a body in the open.

Fourth Power Law. This radiation is focused upon a sensitive thermopile (a supersensitive thermocouple, or a group of thermocouples connected in series) and the current due to the resulting voltage is measured by a galvanometer calibrated in degrees of temperature, or by a potentiometer system.

One such instrument is shown in Figure 47, consisting of a detector tube containing a metal mirror and thermopile, and a portable potentiometer. It may be used in a permanent installation with either a standard recorder

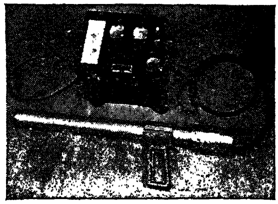


Figure 47. Portable type radiation pyrometer.

or a high-speed recorder. This type of pyrometer is useful for very high temperatures and in corrosive gases, because no parts are directly exposed to the hot gases. A compensating dial is used to allow changes in receiving tubes and to correct for departure from "blackbody" conditions. A water jacket is frequently used around the receiving tube, and for some conditions of pressure and flame the use of a silicon carbide well into which the tube is sighted is recommended. In Figure 48 this pyrometer is measuring the temperature of a rail passing through a rolling mill.

Figure 49 shows the two methods of installing a similar instrument, in which the radiation tube is a compact, self-contained, supersensitive unit. All parts are enclosed in a dust- and moisture-proof case. The thermocouple bulb develops its energy by having focused upon it, through a quartz lens, the radiant heat and light rays from the body to be measured. Since

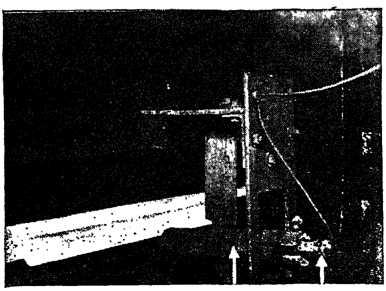


Figure 48. Application of radiation pyrometer to measurement of temperature of rail passing through rolling mill.

the rays are absorbed by a minute, supersensitive thermocouple which reacts almost instantly, the usual time lag is reduced to a few seconds. It can be used with indicators, standard recorders, or high-speed recorders.

A small, self-contained total radiation pyrometer which weighs less than two pounds is made for use at some distance from the furnace, with electrical

operation. The operator is not required to perform any measurements or make any comparisons (as with the usual optical type), so that all readings are independent of "personal error." Temperatures are measured almost instantly and fully automatically by simply pointing the instrument at

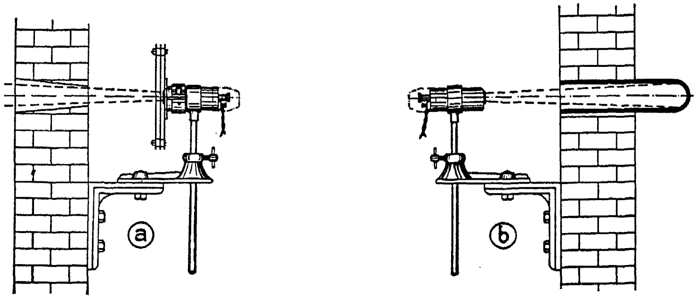



Figure 49. Two methods of installing radiation pyrometer.

the body to be measured. By providing a special clamping device in the indicator, the needle is held at the correct temperature indication until a pressure on a button is applied to permit the needle to return to zero. The pyrometer can be furnished with various scales from 1000 to 3600 deg F.

An entirely new development in fast and sensitive apparatus (Figure 50) is used for measuring such temperatures as those of moving billets in rolling mills. The equipment consists of a thermo-photronic tube, a potentiometer amplifier, and a recorder. In the thermo-photronic tube is mounted a photronic cell which is responsive to the thermal spectrum of a heated mass and which reacts to the thermal spectrum by generating a small electromotive force, which is measured, amplified, and recorded in terms of temperature. The photronic cell consists essentially of a thin metal disc on which there is a film of light-sensitive material. The action of the

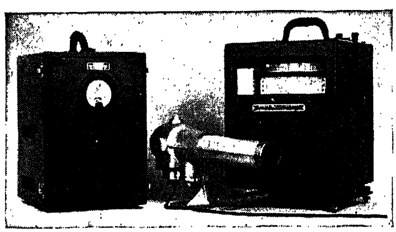


Figure 50. The above equipment, consisting of a thermo-photronic tube, potentiometer amplifier and recorder, is used for measuring temperatures of moving objects.

light in striking the sensitive surface is entirely electronic. No chemical or physical change takes place from the action of the radiant flux, and, therefore, the life of the cell is practically unlimited.

**Low-Temperature Thermometers.** Thermometers and pyrometers for temperatures below 1000 deg F include expansion and resistance types, in addition to the thermocouple types already described.

Expansion thermometers make use of the expansion of a liquid, solid, or gaseous medium to indicate and record temperatures. The usual thermometers depending upon the expansion of mercury or some liquid to indicate temperature are so familiar as to need no comment, except that they are obtainable for temperatures up to 1000 deg F.

A recording pyrometer utilizing the expansion of a gaseous medium is shown in Figure 51. The pressure-sensitive bulb is connected by a capillary tube to the helical tube in the instrument, which is very sensitive to changes in pressure and moves the pen on the chart to record any changes in pressure at the bulb resulting from changes in surrounding temperature.

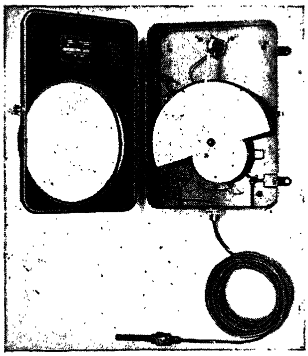


Figure 51. Recording thermometer utilizing expansion of gaseous medium.

The electrical resistance of all pure metals varies with change in temperature, and this fact is used in the design of resistance thermometers for low temperatures. In such an instrument the resistance of a temperature-sensitive conductor is measured by means of a Wheatstone bridge, the temperature-sensitive conductor forming one arm of the bridge.

**Temperature Control Devices.** The purpose of any automatic temperature-control device is to hold the temperature as close to the set value as possible at all times, in spite of wide variations in heat demand. For continuous furnaces where the loading is fairly steady, or for batch-type furnaces having a short holding time at control temperature, the simple "on and off," or two-position controller will provide satisfactory results at minimum investment cost. In many applications, however, the heat demand fluctuates rapidly, and additional control features are desirable. This requirement led to the development of controls with more than two settings, and later to various ingenious methods for anticipating the demand for heat in the furnace.

**Two-Position Controllers.** The essential parts of this type of control are contacts in the standard indicating or recording pyrometers or thermometers already described, and a valve or contactor for regulating the fuel or electric input to the furnace at two rates as called for by the closing

of the contacts in the pyrometer. The pyrometers are called indicating or recording *controllers* when fitted with contacts for the operation of any control valves or relays. Where more than 20 amperes are required, a relay is used to avoid overloading of contacts in the pyrometer.

A sensitive device which eliminates mechanical parts is shown in Figure 52; its operation depends upon the fact that the plate current of an electronic tube in the oscillating condition is determined by the amount of grid excitation it receives. A no-contact operation is obtained when a small disc which is mounted upon a pointer approaches a small coil, which may be moved to any position on the scale from outside the case. The electronic tube is instantly affected when the indicating and controlling pointers coincide. The effect is transmitted through a relay to the two-position fuel control valve. This type of control can also be adapted to almost any type of multiposition or proportioning control.

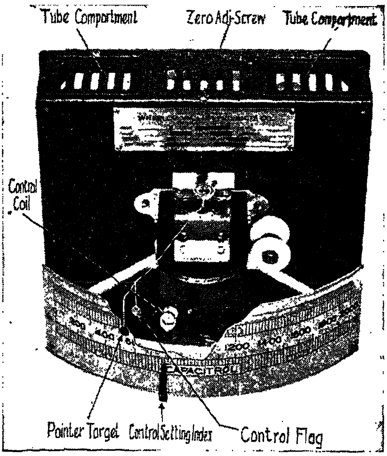



Figure 52. Temperature controller utilizing principle based upon electronic tube action.

The valve for regulating fuel rate may be either solenoid-actuated, as shown in Figure 53, motor-driven as in Figure 54, or air-operated. In the

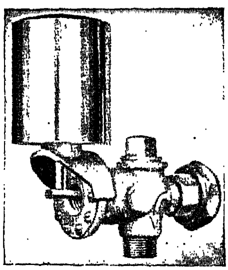


Figure 53. Solenoid-operated valve.

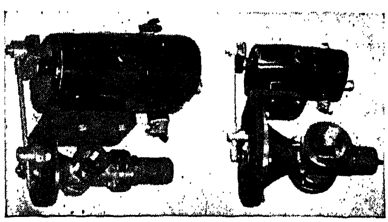


Figure 54. Motor-operated fuel valves for oil at left; and gas at right.

case of the latter, a solenoid pilot valve operated by the pyrometer controls the movement of the air-driven fuel valves. All two-position valves should be supplied with limiting adjustments to control the maximum and minimum rates of fuel flow to suit furnace conditions. Figure 55 shows a cross-

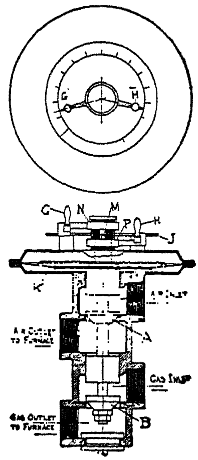


Figure 55. Cross-section of regulating valve.

section of a regulating valve with levers for adjusting maximum and minimum openings. An automatic fuel input throttle may be attached to this valve for full operation during heating up; it holds to a predetermined maximum position the instant the furnace reaches the set temperature.

A valve for controlling low-pressure air supplying single-valve proportional fuel-air mixing devices (see atmosphere control discussion below) may be diaphragm-operated by air from the blower supplying combustion air to the burners if a small solenoid is provided to control the air to the diaphragm. However, some form of motor-driven valve is usually preferable to any of the devices which depend upon a solenoid for operation. Another common arrangement of control valves is that in which the valves for both fuel and air are mounted on the same motor shaft.

Recorder controllers operating on the gas expansion principle have already been described for low-temperature measurement, and may be equipped with electrical contacts to operate a two-position valve of any type. Figure 56 shows a controller of simple form based upon the differential expansion of a metal tube and an inner member, to actuate snap-action electrical contacts through a simple lever system. These instruments will operate either two-position fuel valves of any type or the contactors of electric furnaces.

**Multi-Position Controllers.** Following the adoption of two-position controllers for all kinds of industrial heating equipment, multi-position controllers were developed to meet the need for closer regulation. The

first development was the three-position controller, with three contact points in the pyrometer. The rate of fuel flow then alternated either between maximum and medium or between medium and minimum settings, depending upon the demands of the furnace. This was an improvement over two-position control for batch furnaces with high demand while heating and low demand while soaking. Further development before anticipating control was introduced included instruments for more than three points.

The three-position control still occupies a useful position between the two-position and anticipating control, for such applications as certain underfired chambers and for radiant-tube heaters, where a gradual reduction of gas flow as obtained with anticipating control will upset temperature uniformity in the chamber or tube. Under such conditions, alternating between maximum and medium or between medium and minimum settings is definitely to be preferred.

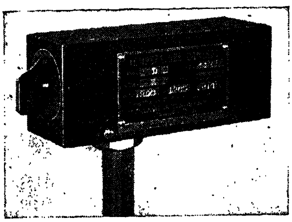


Figure 56. Controller operating on differential expansion principle to actuate snap action electric contacts.

**Proportioning or Anticipating Controllers.** The ideal in temperature control for most applications is obviously a perfect balance between the heat required in the furnace and that delivered to the furnace, and the maintenance of this balance at all times, regardless of conditions. It is clear that the two-position and the multi-position devices only approximate this ideal under conditions where the fluctuation in heat demand is wide or rapid. To approach the ideal more closely, a number of ingenious devices have been developed.

To understand the operation of these, it is necessary to know the meaning of several terms commonly used in describing them.

In any consideration of ideal balance it is necessary to consider the effect of "process lag," which may be defined as the time interval between the moment the control valve setting is changed and the instant the control instrument measuring element feels the effect of the change. This lag is different for every furnace or process, and for good control it is essential that the "sensitivity" and "throttling range" of the controller will suit the process lag for any application. "Sensitivity" is the ability of the instrument to respond to small changes of the measured variable and "throttling range" is the amount of movement of the controller pen or

indicator (number of degrees of temperature) which will cause the control valve to move from zero to wide-open position. It is sometimes expressed in percentage of total degrees of temperature for which the controller is designed.

One of several devices for anticipating and correcting for temperature change (Figure 57) is connected to a two-position pyrometer controller, and functions to change the control valve in the proper direction before the temperature reaches the control point in the case of either rising or falling temperature. To correct for the effect of temperature lag, the instrument imparts to the thermocouple circuit an additional voltage, so as to deflect the galvanometer slightly beyond the position it would occupy in relation to actual thermocouple temperature. The instrument does not record, and when a record is required, a separate recording pyrometer must be provided.

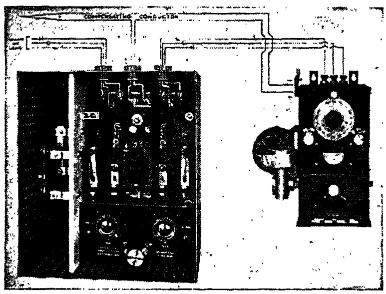


Figure 57. Device for anticipating and correcting for temperature changes.

Most proportioning controllers operate on the principle that the control valve changes in proportion to the amount of deviation of the temperature from the control setting. With these instruments the characteristic record is practically a straight line, but for some types of process lag the temperature will tend to wander from the control setting, although it remains within the throttling range of the controller if this range has been properly set.

With one design of proportioning controller, which utilizes a mirror galvanometer with light beam and photoelectric cell to increase speed of operation by eliminating mechanical friction, the correction of the control valve commences as soon as the temperature deviates from the control setting and proceeds in proportion to the deviation in the usual manner. Superimposed upon this action are periodic tests to determine whether the temperature is away from the control point, and application of a resulting corrective action on the valve. The combination of two independent actions on the valve produces a control which effectively reduces "hunting" or overshooting, and which can effect a rapid return from abnormal conditions.

Figure 58 illustrates a combination of unit mechanisms suitable for pro-

portioning control, including a pyrometer controller of potentiometer type, relay detector, and control valve mechanism. The instrument corrects the valve in proportion to deviation from control setting, but includes automatic droop corrector, or reset device, which provides correction of the control point if, due to unusual process lag conditions, the temperature

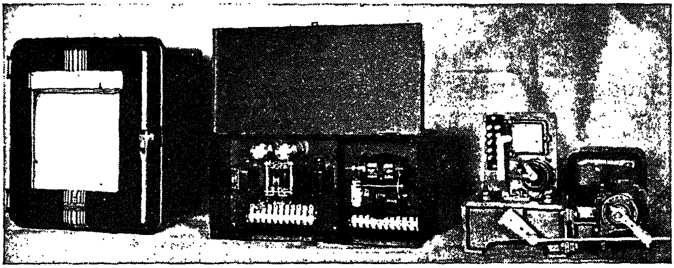


Figure 58. Combination of unit mechanisms for proportional control, including: (a) pyrometer controller of potentiometer type, (b) relay detector, and (c) control mechanism.

wanders away from the control point, within the throttling range. Figure 59 shows diagrammatically the operation of the control unit. Automatic droop correction is generally preferable to manual droop correction, where the operator can shift the center of the throttling range by means of a knob when a sustained change in operating conditions causes the pyrometer to balance just off the control point. It has been the author's experience

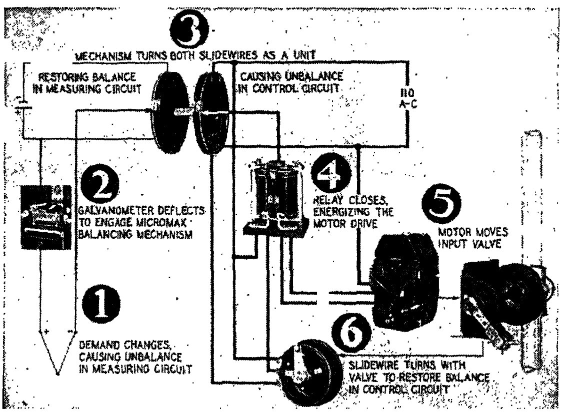



Figure 59. Diagram illustrating operation of proportioning control system shown in Figure 58.

that where this knob is available to the operator, the tendency is to revert to hand operation of the furnace by continual adjustment of the knob, so that all advantages of automatic control of temperature are lost and the investment for control equipment is wasted. With automatic droop correction this objection is eliminated.

In an ingenious proportioning control application for burning fuel oil, (Figure 60) the control floats to a balance with the heat demand through the joint action of the pyrometer, an anticipating device, and a solenoid valve controlling a diaphragm-operated pilot valve, which in turn positions an air-operated power diaphragm. This air-operated power diaphragm operates the air valves on the burners through a system of levers, and also operates the adjustment levers on an oil-metering pump, which replaces all oil valves in the system and therefore entirely eliminates the clogging

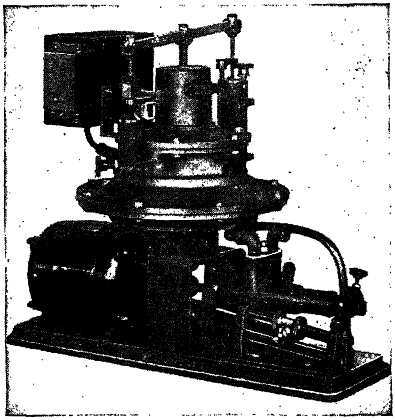


Figure 60. Floating type valveless controller, feeds oil by power-driven metering pump of automatically adjustable delivery.

difficulties which are common to most oil-burning control systems. This control adjusts from maximum to minimum for temperature changes within a narrow range, so that the temperature is held close to the control setting. The anticipator acts upon mechanical parts of the pyrometer, so that the temperature indication and record are not disturbed.

Another controller operates the fuel valve or electric switch on a time interval basis, the length of time the heat is on being proportional to the heat input required to bring the charge to control temperature (Figure 61). The heating rate is controlled by the "on and off" method during each one-minute interval. For example, when the control is set at 40 per cent, the heat is on 24 seconds and off 36 seconds. The "on and off" impulses are obtained through a mercury switch mounted on a carriage, which rides on an especially shaped horizontal cylindrical cam, rotated at one rpm. The carriage is moved across the cam by a spiral worm operated either manually or automatically. The position on the cam determines the percentage of "on" and "off."

On the manual instrument the operator sets the rate by turning a knob on the side of the case. The automatic control is used in conjunction with a control pyrometer. Here the rate is set by a reversible motor coupled to the worm and energized by the pyrometer contacts. As heating conditions

change, the setting is immediately and automatically shifted to compensate. When the entire charge has reached temperature, the rate of heating will be reduced to the amount required to hold the furnace at temperature.

Still another development in control departs from the principle of adjusting valve opening from temperature deviation (Figure 62). In this system a standard proportioning valve is driven by a reversible motor. The switch governing minimum valve opening is mechanically fixed, while the switch governing maximum valve opening is automatically adjusted by means

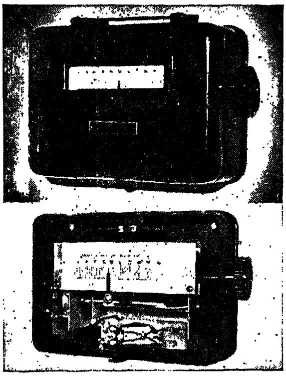


Figure 61. Controller which operates fuel valve or electric switch on time interval basis in proportion to heat input required.

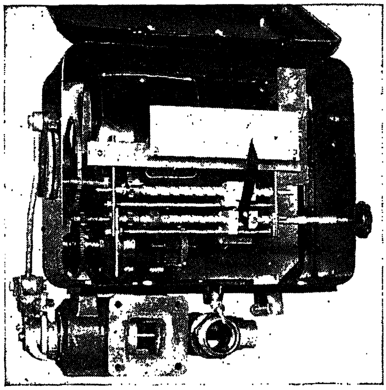


Figure 62. Throttling controller in which maximum valve opening is automatically changed, the amount of change being proportional to time required for recovery.

of the reversible motor, operated by contacts in the pyrometer. As soon as the temperature deviates from the control setting the maximum valve opening is automatically changed, and the amount of change is proportional to the time required for recovery. When the temperature rises, the heat is shut off entirely while the valve is adjusted, so that overheating is practically eliminated.

Another development in proportioning fuel to furnace demand is operated without contacts. When a flag on the temperature pointer approaches the control setting it enters between the coils of a revolving condenser. When the flag enters between the coils, the heat supply to the furnace is turned off and on periodically, and the amount of flag area between the coils determines the ratio of on and off time. Thus, if the flag is 50 per cent in the coils the furnace heat is turned on for half of the time. When the pointer flag finally reaches the control setting, the heat is turned completely off, and as the temperature drops from the control setting the heat is again turned on as a portion of the flag area leaves the coils.

**Safety Control Devices.** Several types of devices are now available for promotion of safer operation of furnaces, ovens, and other heating equipment. The use of flame-actuated automatic combustion safeguards has increased rapidly as the result of activity by the insurance companies. The purpose of these devices is to cut off the fuel supply in the event of flame failure, in order to prevent the relighting of an explosive mixture.

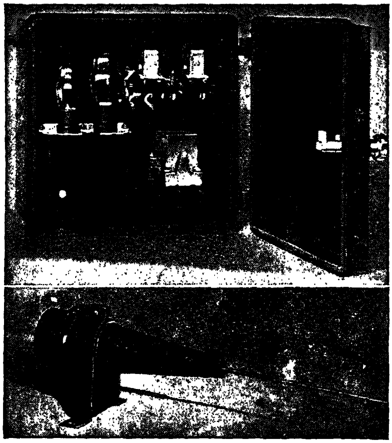


Figure 63. Combustion safeguard equipment which employs a flame sensitive electrode shown below, in combination with a cut-off unit or a relight unit.

One system is illustrated in Figure 63 and depends for operation on the fact that flame will conduct electricity. The system consists of a flame unit, and either a cut-off unit or a relight unit. The flame unit is an alloy rod projecting into the flame to make an electrical circuit with it. The cut-off unit consists of radio vacuum tubes which rapidly operate the fuel valve relay to close the fuel valve in event of flame failure. The relight

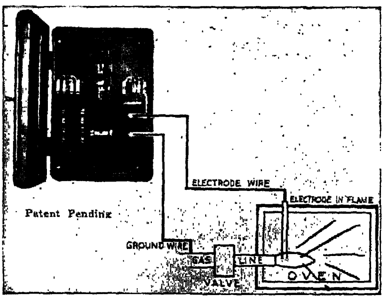



Figure 64. Automatic gas shut-off which consists of electronic tube device which operates on principle of conduction of electric current through the flame.

unit delays the shut-down if the flame falters but recovers within 60 seconds. If this time interval is exceeded the shut-down is final, and requires manual reopening of the fuel valve.

Another flame conduction device (Figure 64) for the protection of gas- or oil-fired furnaces is an electronic tube arrangement which instantly

shuts off the main fuel supply if the pilot or burner flame fails. A high-temperature alloy rod is placed in the flame to conduct an electric current from it to the burner orifice. Failure of the flame breaks the circuit and causes the relay to operate. Failure of any portion of this device, or a short-circuit, closes the fuel valve and requires manual attention for relighting.

Safety units which will automatically light the burners of gas-fired ovens or furnaces, as well as eliminate the hazards resulting from failure of pilot flames, are also available. Provision against failure of air or gas supply can also be made by the installation of simple accessories. Safety lighting

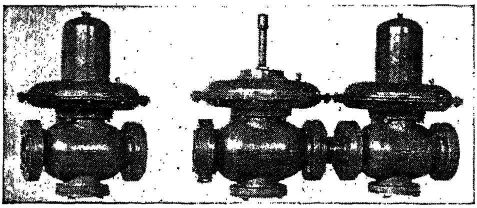


Figure 65. Valve arrangements which will automatically shut off gas supply in case of failure of either gas or air.

units consist of two parts, *i.e.*, a pilot thermocouple and a control cabinet. A switch is provided which places the unit in operation. The operator then starts the fan; at this point the safety device takes charge, and there follows a cycle of operations in lighting the burners which cannot be changed. When the fan is started, the air flow relay is actuated by the flow of air, and sets the safety unit in actual operation. The fan operates for a predetermined period of from 5 to 10 minutes to exhaust any gases or explosive vapors which may have collected. At the end of this period the pilot gas valve opens and the spark plug ignites the pilot. The pilot heats the thermocouple, and when conditions are correct for safe ignition of the main gas burners, the main gas valve opens and the burners are ignited.

If the pilot flame fails, or if the source of electricity is interrupted, the gas supply to both pilot and burners is shut off, and the furnace cannot be fired again except by repetition of the cycle described.

In another type of combustion safeguard, the detector also consists of a thermocouple influenced by the pilot flame. Should the pilot become extinguished the control instrument closes the pilot and main gas valves. A time delay relay is introduced to start automatically after a purging period to allow elimination of gases.

A photoelectric alarm device for operating a signal light or siren upon detection of smoke in an oven or furnace is also made. It consists of a photoelectric cell upon which a light source is focused. Smoke passing between the light and the cell causes a loss in generated current which permits a relay to operate an alarm.

One of several types of valves which will automatically shut off the gas supply in case of pressure failure is shown in Figure 65, which is a dual

valve arrangement to shut the gas supply in case of failure of either gas or air pressure. These valves remain closed until the release latch has been manually reset.

A temperature-limiting device using a thermocouple may be set to close a valve or operate a warning signal at any set temperature. Such an instrument may replace the gold fuses used in electric furnaces or may be used

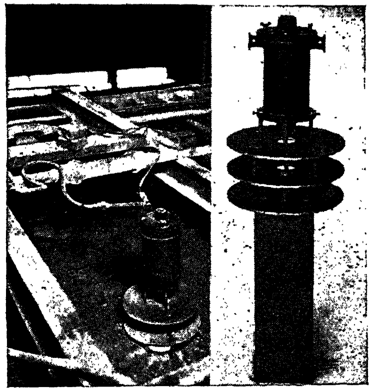


Figure 66: Roof temperature control which utilizes a radiation type of detector.

to protect costly alloy parts in fuel-fired furnaces. Another common use is to protect the roof of open-hearth furnaces. Such a detector for limiting roof temperature is illustrated in Figure 66.

**The Control of Furnace Atmosphere**

The subject of combustion control is closely related to temperature control, and the application of combustion-control equipment to industrial furnaces is equally interesting to combustion and furnace engineers and to metallurgists.

Just as in the case of temperature control, the application of combustion control to metallurgical furnaces is becoming rapidly more necessary and important. Makers and users of ferrous metals are realizing that the heating of these products is a chemical as well as a physical process. The relation of temperature to metallurgy is now well understood by all departments of the mills and factories, but the relation of atmosphere in furnaces to the chemistry of metals is not so well defined. Upon first glance, the problem appears to be simple, because relatively few elements are involved in either the metal or the gaseous atmosphere. The reaction of these elements is controlled by relatively few conditions, including temperature, time, and degree and frequency of contact between the elements involved. (This has been discussed at length in Chapter 1.) As in the game of dice, however, the possible combinations of a few numbers are sufficient to be endlessly interesting, and the comparison may be continued by stating

that the chemical results, including surface condition of the metal, scale loss, and decarburization are no more consistent at present than are the results in the familiar game of chance.

The practical control of these chemical reactions and a better understanding of them will definitely follow the adoption of atmosphere- and pressure-controlling equipment.

The principal factors which affect the atmosphere in any metallurgical furnace are:

(1) Degree of mixing of fuel and air.
(2) Ratio of air to fuel.
(3) Pressure in the furnace.

By degree of mixing of fuel and air is meant the intimacy of contact between the particles of the fuel and of the air, which is a function of the size of the particles, the velocity of the fuel and of the air in contact with each other, and the turbulence of the reaction. The air-fuel ratio is the relative quantities of combustion air and of fuel supplied to the furnace. The pressure in the furnace regulates the quantity of air drawn into it in the case of a draft or negative pressure in the furnace.

The degree of mixing of fuel and air is controlled by burner or furnace port design, discussed in Chapter 2. Control of air-fuel ratio and of furnace pressure is accomplished by control equipment.

**Air-Fuel Ratio Control.** An outline of the principal methods of air-fuel ratio control is shown in Table 25 (see also Figure 18 and Table 22 in Chapter 2).

Two valve systems for oil and gas comprise a fuel valve and an air valve which are adjusted in one of several ways, none of which is automatic in the true sense. These methods include:

(1) Manual setting, for any fuel rate, of fuel and air by appearance of the flame or by analysis of the atmosphere.
(2) Setting of the high and low positions of air and fuel valves driven by a two-position automatic temperature control motor.
(3) Adjustment at average rate of flow of air and fuel valves driven by proportioning temperature controller.

This type of ratio control for gas applies only to two-pipe systems, including luminous, blast-type, and nozzle-mixing burners. In the case of fuel oil, the metering of oil by a metering pump has already been mentioned under temperature control. This type of control eliminates difficulties from clogging of valves and permits more accurate control of air-oil ratio.

A duplex valve unit for maintaining a constant ratio between fuel oil and steam can be used with steam-atomizing oil burners. This unit prevents an atmosphere high in detrimental water vapor, which often results from

Table 25. Principal Methods of Ratio Control

| Fuel | Method | Operation |
|---|---|---|
| Fuel oil | Two-valve | High and low ratio manually adjusted, and oil and air valves changed by one control motor |
| | Cross-connected | Variation in air pressure caused by operation of control valve in air line is transmitted to oil flow regulator to maintain ratio |
| | Valveless | Variable stroke metering pump actuated by air pressure to maintain ratio |
| Clean gases | Two-valve | Same as for fuel oil above |
| | Area valves | Fuel and air valves with common rotation and adjustable width to maintain constant ratio by constant relation between port areas |
| | Cross-connected | Governor in gas line actuated by air pressure variations in air line |
| | Balanced flow | Pressure drop through orifices in air and gas lines are kept in balance by automatic operation of a valve in either the air or gas line |
| | Low-pressure inspirators | Air inspirates gas in constant proportion to air flow |
| | High-pressure injectors | Air is injected in constant proportion to amount of gas flowing |
| | Fan-type mixers | Air and gas inlet to premixing fan are adjusted to desired ratio |
| | High-pressure air mixers | Gas and atmospheric air are injected by high pressure air. Used for small units where blower is not available |

the control of oil only when operating furnaces with steam-atomizing burners.

The area valve is applicable to two-pipe systems. The gas and air or oil and air valves are of the rotating-sleeve type on a common shaft with adjustable width of port opening, and may be hand-operated or motor-driven for automatic temperature control. The fuel and air ports are adjusted for an average fuel rate, and will maintain this ratio over a fairly wide range if the pressure of the fuel and air is kept constant by regulators and by constant-pressure blowers. The range of accuracy with this simple type of control is set by the point at which the relative dimensions of the ports change to an extent sufficient to affect seriously the coefficient of discharge.

The proportioning of air to gas by high-pressure injectors is necessarily approximate and varies over any considerable range of burner turn-down. The ratio is also affected by furnace pressure variations.

The cross-connected governor system is illustrated by Figure 20 in Chapter 2, in which the air pressure between the air-control valve and the burner or burners is transmitted to one side of the gas (or oil) governor. By adjustment of a bleeder in this small connection line, the ratio is adjusted for an average fuel rate and will be maintained over a fairly wide range. The flow of fuel to the furnace is regulated by adjusting the air

valve only, either manually or by any of the various types of automatic temperature control valves.

One of several makes of inspirating low-pressure ratio control is illustrated by Figure 22 in Chapter 2. In this system the gas is regulated by a zero governor of very sensitive design. The function of this governor is to balance the suction of the burner or burners (which is proportional to air flow) against the gas line pressure, to keep the pressure in the regulator at zero. With the gas pressure at zero and the suction proportional to air

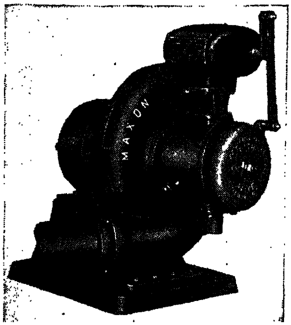



Figure 67. Premixing unit, motor-driven, with proportioning valve, for furnishing desired air-gas ratio.

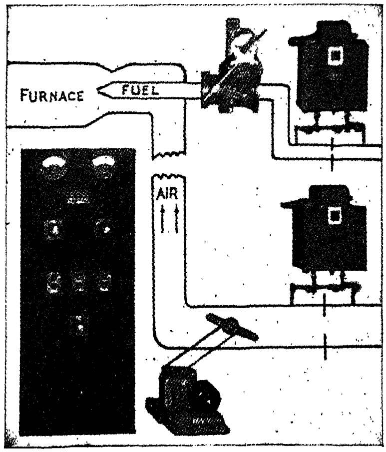



Figure 68. Schematic diagram of metered combustion control equipment which proportions fuel and air to a common loading force.

flow, it follows that the gas flow will also be in proportion to the air flow. It only remains to adjust a resistance for an average flow rate, and the desired ratio will be maintained over a wide range. In this case, the temperature is controlled by regulation of the air only.

Figure 67 shows one type of premixing fan with a proportional valve in the suction side of the fan. The resulting proportioned mixture is delivered to a manifold for delivery to one or more burners, and the temperature-control valve is in the mixture line. Safety devices must be used in such systems to prevent back-firing to the mixture in the manifolds. In these machines, the suction of the compressor draws air and gas into the compressor. Proportioning pressure valves and regulation of orifices are used to control the ratio of air to gas delivered by the controller unit.

A ratio control which proportions both fuel and air to a common loading force (4 in Figure 18) is illustrated in Figure 68. Rate of fuel supply is metered by a controller which balances differential pressure from a fuel

orifice against an electric control current. Contacts at the controller actuate a motor-operated fuel valve as required to maintain the balance. An air flow controller balances air supply against the electric control current in a similar manner by actuating a motor-operated air butterfly valve. The furnace operator sets the desired firing rate by turning a rheostat which controls the amount of electric current.

Figure 69 shows a proportional mixer for use where high-pressure air alone is available. In this case the high-pressure air injects gas at zero pressure and atmospheric air for combustion through a Venturi throat.

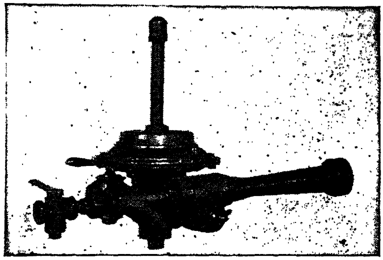


Figure 69. Proportional mixer used where high-pressure air only is available.

The relative quantities of each may be adjusted and will remain in proportion for any rate of flow of high-pressure air over a reasonable turn-down range. Adjustment of temperature is accomplished by regulation of the high-pressure air only.

An example of the balanced-pressure method of maintaining a constant ratio (also 4 in Figure 18) is shown diagrammatically in Figure 70 and the regulating device is shown in Figure 71. The air valve is actuated by

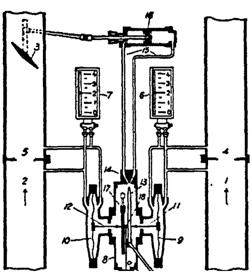


Figure 70. Diagram of balanced pressure method for maintaining a constant flow ratio. Equipment consists of (a) Regulator, (b) Control Cylinder, (c) Pump Unit.

means of an oil-hydraulic cylinder, with oil supplied to either side of the cylinder through a jet pipe, the position of which is determined by diaphragms connected to the gas and air orifices. If the cylinder-operated valve is in the air line, the temperature is regulated by a valve in the gas line.

Another form of this class of air-gas ratio controller incorporates two differential diaphragms, one across an orifice in the air line, and the other across a manually operated ratio valve in the gas line. Diaphragm-operated gages indicate the air and gas flow, and the calibrated controller may be

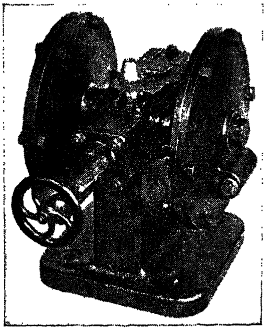


Figure 71. Regulating unit for the balanced pressure method of control shown diagrammatically in Figure 70.

set for any ratio. The forces from the air and gas diaphragms operate on a differential beam which actuates the control air pilot valve. To change the ratio, the operator has only to change the manually operated ratio adjusting valve in the gas line.

**Furnace Pressure Control.** The control of furnace pressure is vitally necessary in any case where furnace atmosphere is important, because only by pressure control can the entrance of free air from the atmosphere be prevented. This free air is both a scaling and a decarburizing agent, so that the benefit of ratio control can be realized only in conjunction with some form of pressure control.

Several methods of semi-automatic pressure regulation may be applied to any existing furnace at small expense, which will partly take care of the exclusion of free air. The first step is to construct a manifold around all flues; in the manifold there should be one vent, provided with a damper. The damper may be electrically operated or air-operated with an electric valve. A limit switch is provided at each door, so that the opening of any door will cause the damper to close. A further refinement comprises a limit switch on the fuel control valve, so that when this valve is closed to a low setting, either manually or by automatic control, the flue damper will close and maintain pressure in the furnace at the low rate of firing.

The best results are obtained by the use of one of the forms of fully automatic pressure control. These controllers are actuated by the actual pressure in the furnace and will accurately hold this pressure to within a few thousandths of an inch of water pressure.

One such controller is shown in Figure 72. The control device comprises a pressure bell of relatively large area connected to the furnace. The movement of this bell in response to changes in furnace pressure actuates

a balance beam which carries electric contacts. These contacts, through a relay, energize a motor drive which moves the damper to bring the beam to the desired position at all times. A micrometer screw for setting the desired furnace pressure is provided at the upper right of the case.

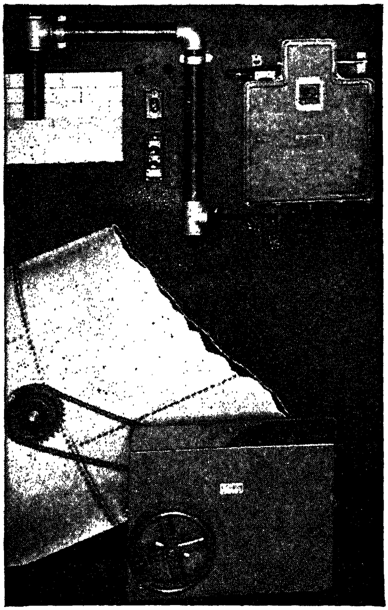


Figure 72. Schematic arrangement of furnace pressure controller installation. Controller connected to furnace is shown above, while motor for movement of damper is shown below.

Another pressure controller operates on the same principle as the ratio controller already described (Figure 70). In this case, the pressure of the furnace operates a diaphragm connected to the oil-jet pipe. The movement of this jet pipe directs the pressure oil from the pump to either side of the oil-hydraulic cylinder which actuates the flue damper of the furnace. The movement of the damper, by affecting furnace pressure, keeps the jet pipe centered, and the relation of this center position to furnace pressure may be accurately adjusted to the desired pressure. A sensitive gage should be provided to indicate the pressure in the furnace.

Figure 73 is a schematic arrangement, where the furnace pressure actuates a sensitive diaphragm which acts upon an adjustable weigh-beam, regulating an oil pilot valve which supplies oil under pressure to an actuating power cylinder. This unit is complete with damper-positioning indicator, manual control knob, pressure setting adjustor, pressure recorder, and oil pump unit for supplying oil pressure to the power cylinder.

Another device regulates a damper by means of compressed air. The unit comprises an escape valve transmitting a variable pneumatic impulse in accordance with the position of a diaphragm which is actuated by the furnace pressure. The impulse regulates the pilot valve supplying air

to the cylinder which actuates the controlling damper. Means are also provided for regulating rate and degree of compensation for the time lag inherent in the system under control.

Still another electrically operated pressure controller operates on a unique principle. The furnace pressure actuates a sensitive diaphragm attached to adjustable contacts, which are connected to the two solenoids on the drive unit. This unit comprises a continuously running motor which operates a reversible planetary gear transmission connected to the damper

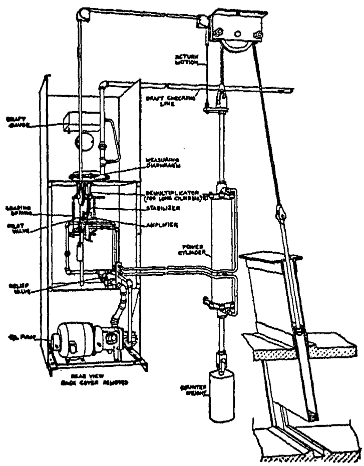



Figure 73. Schematic arrangement of the furnace pressure controller.

lever. The direction of rotation of the output shaft of the transmission is determined by which solenoid is energized. The function of these solenoids is to engage and hold the ring gear of the transmission. Action of this device is extremely rapid, with resulting sensitivity of control.

Another air-operated furnace pressure controller consists of a recording pressure controller and an air cylinder unit for operating the furnace damper. The controller has two oil-sealed bells balanced on a beam and connected to the pilot valves operating the regulating cylinder. A double connection feature at the furnace tap is designed to eliminate the effect of high temperatures of the pressure pipe at the furnace.

A full value of the different controls which have been described cannot be realized without auxiliary instruments for accurately adjusting the control and for observing the results of their operation. Among the instruments required are flowmeters for fuel and air, pressure gages, and analyzers for furnace atmosphere.

**Flowmeters.** Flowmeters may be of the indicating, recording, or integrating types, and in most cases operate from the differential pressure across an orifice, Venturi tube, or Pitot tube located in the gas or air line. The principle of operation from this pressure drop may be either mechanical or electrical.

In its simplest form a flowmeter consists of a U-tube containing water or mercury and connected to the two sides of the orifice. The difference in level in the U-tube is a measure of the flow when used with the proper calibration chart for the conditions.

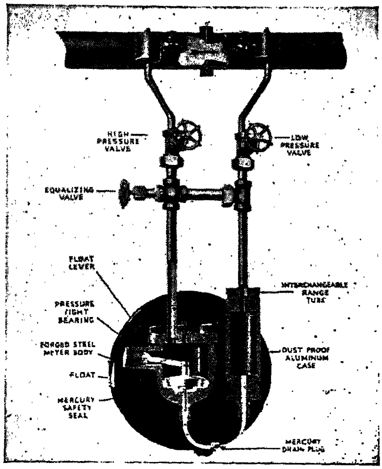



Figure 74. Mechanically operated flowmeter. Cut-away sections illustrate principle of operation.

The usual mechanical type of flowmeter simply connects the movement of the mercury to a properly calibrated pointer or pen device by means of levers (Figure 74). The movement of the mercury is transmitted to the pointer by means of the float and lever shown in the illustration.

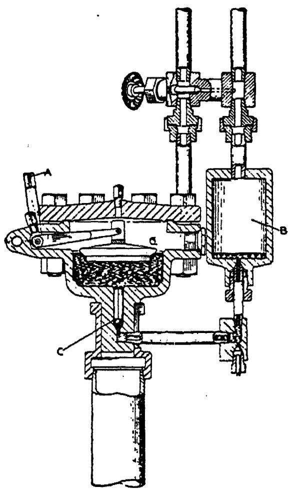



Figure 75. Illustrating principle of operation of the mechanically operated flowmeter.

In another mechanical flowmeter a float transmits the movement of a column of mercury to the indicating, recording, and integrating device. Figure 75 is a schematic drawing illustrating its principle of operation.

A mechanically operated flowmeter incorporating the Ledoux bell principle is illustrated by Figure 76, showing the exterior front view and a rear view with section through the flow-measuring mechanism. Referring to

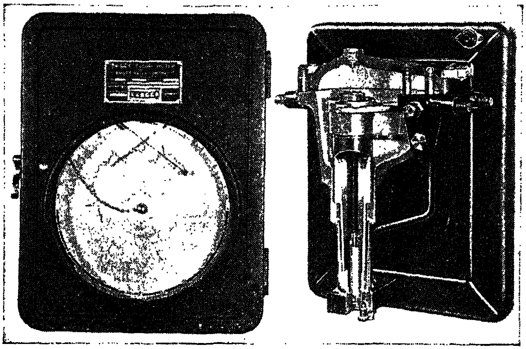


Figure 76. Front and rear views of mechanical flowmeter incorporating Ledoux bell principle, with section through flow-measuring mechanism.

this rear view, it will be noted that the bell is of a parabolic shape and is provided with a standpipe along its vertical axis. The purpose of this pipe is to transmit the inlet pressure through the mercury in which the bell floats and to apply it to the underside of the bell. The outlet pressure is applied above the bell, so that it takes a position corresponding to the rate of flow through the line. The parabolic shape of the bell provides ample power and permits the use of a uniformly graduated chart. The meter requires no outside source of power for its operation.

Still another mechanical meter is illustrated in Figure 77, and comprises a flexible metallic bellows in conjunction with a calibrated spring to balance the differential pressure across the orifice, rather than the mercury column used in the instruments just described.

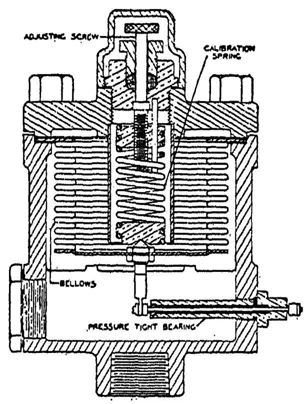



Figure 77. Sectional view to illustrate operation of the mechanical flowmeter.

A unique principle is employed in the meter of Figure 78. In this device the mercury column on the high-pressure side of the orifice is placed between an electric light and a sensitized chart. When there is flow through the

orifice, the mercury column falls, allowing the light to strike the chart and register the flow. The instrument has no moving parts or electrical contacts, which makes the operation exceedingly simple.

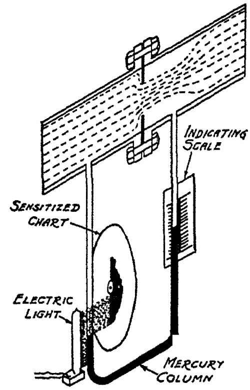



Figure 78. Flowmeter in which the height of mercury column is indicated on a scale and is also recorded on a sensitized chart.

Electrically operated flowmeters are made in several different forms. One principle of operation (Figure 79) is that of the inductance bridge, in which the float transmits the movement of the mercury column to the armature in the induction coil; by electrical connections the movement

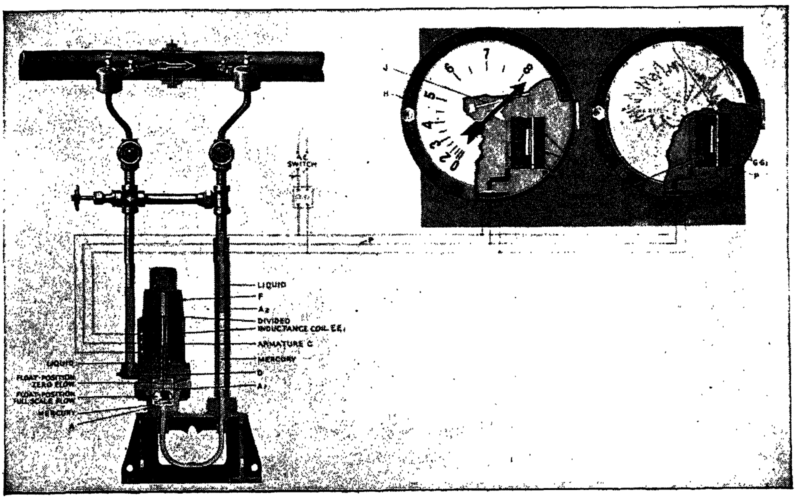



Figure 79. Electrically operated flowmeter which employs the inductance bridge principle.

may be indicated and recorded at one or several different and remote points. Features of this instrument are provision for preventing the mercury from blowing out as the result of violent pressure changes, and a

quickly replaced range tube for changing the range of the instrument without changing the orifice in the pipe line.

In another electrically operated flowmeter (Figure 80) one side of the mercury tube connects with a contact chamber containing a series of contact rods of different lengths. As the mercury rises, the number of

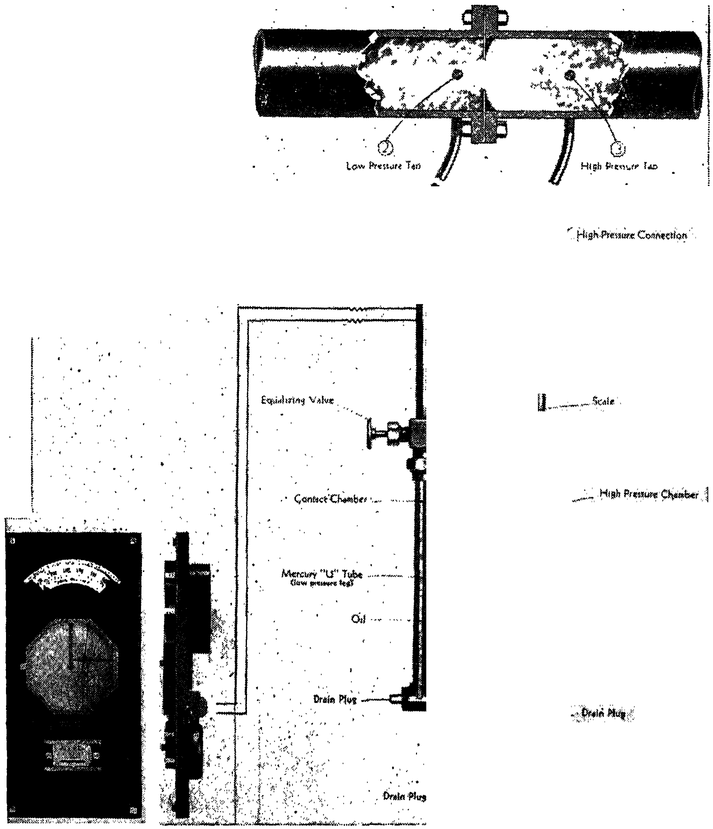



Figure 80. Electrically operated flowmeter in which rising mercury contacts with series of wires causing change in electrical resistance which is recorded in terms of flow.

contacts with the mercury becomes greater; this increases the resistance in the recorder circuit. The principal features include provision for blowing of the mercury, remote indicating, recording, or integrating, and absence of floats and levers in connection with the mercury column.

Pressure gages are a necessity in connection with furnace-pressure control, and may be in the form of either indicators or recorders. For these low

pressures, of the order of 0.001 inch of water column, the operating principle of most of these gages is the movement of a pressure bell connected mechanically to the pointer or to the pen arm. A gage with a chart range from minus 0.15 inch of water to zero to plus 0.05 inch of water is recommended for furnace-pressure measurements.

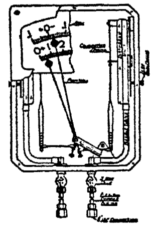


Figure 81. Diagram illustrating principle of operation of indicating pressure gage.

Figure 81 illustrates a pressure gage suitable for industrial furnace pressures, and shows the manner in which the movement of the diaphragm is transmitted to the pen arm by means of a sensitive linkage.

In the determination of furnace atmospheres, the familiar method is by hand-operated Orsat apparatus, but this device requires some skill and considerable time for accurate operation. To assist in determining furnace atmospheres, several forms of meters for measuring $CO_2$ are available. One form in which the instrument automatically performs the same

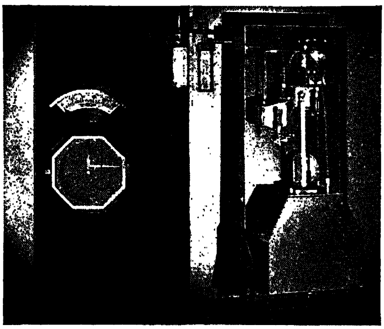


Figure 82. Front and rear views of $CO_2$ recorder.

chemical operations as the Orsat is illustrated in Figure 82, which shows the front and rear view of the machine.

A mechanical $CO_2$ meter is shown in Figure 83. This device depends upon the variation in specific weights of flue gases with varying contents of relatively heavy $CO_2$. A motor-driven fan forces the gas against an impulse wheel as shown in Figure 84 and forces air against a similar wheel to avoid the effects of variation in fan speed, temperature, humidity, and atmospheric pressure. The difference in force of the air and the gas is the measure of the $CO_2$ content of the gas.

An electrical $CO_2$ meter, based upon the thermal conductivity of gases

is shown in Figure 85, in which the varying thermal conductivity of gases with varying $CO_2$ contents is employed to determine the analysis. This is determined by the resistance of wires surrounded by a reference gas

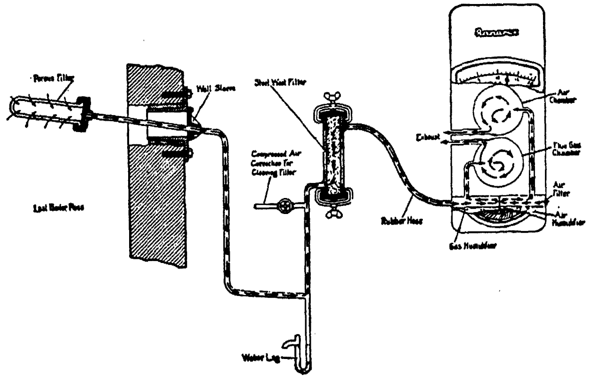



Figure 83. Diagrammatic arrangement of mechanical $CO_2$ indicator.

and by the unknown combination; these wires are connected to a Wheatstone bridge. The apparatus may be used also for quantitative determinations of other gases.

In another instrument for determining the percentage of combustible gases in atmospheres which are neutral or reducing in character, the flue

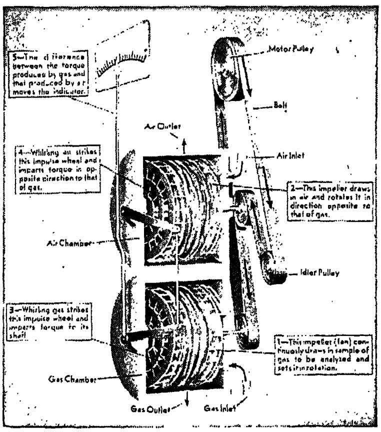



Figure 84. Cross-sectional view of mechanism shown diagrammatically in Figure 83, by means of which the $CO_2$ content is measured and indicated.

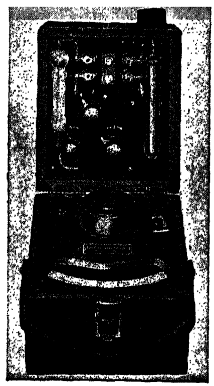


Figure 85. Electrical $CO_2$ meter, the operation of which is based on the thermal conductivity of gases.

gas is mixed with air and burned in contact with a hot platinum wire. This wire forms one leg of a Wheatstone bridge and a platinum wire in contact with air forms another leg. The varying resistance of the wire in

contact with catalytic combustion of the combustible elements of the flue gas is measured and converted to a percentage of combustible gas in the flue gas.

Another instrument for determining atmospheres resulting from either complete or incomplete combustion is of the potentiometer type, and operates on the principle of measuring the thermal conductivity of the gas. The chart is divided into two parts, one for complete combustion and the other for incomplete combustion, accomplished by using different electrical sensitivities in a Wheatstone bridge.

A discussion of combustion control equipment is not complete without a brief mention of bright annealing, which is discussed in detail in Chapter 1. The above discussion has been devoted to methods for controlling the atmosphere in fuel-fired furnaces, to maintain an atmosphere analysis best suited to the product to be heated. By such control copper may be bright-annealed in an open furnace; but other metals cannot be heated without some form of oxidation, since $CO_2$ and water vapor are oxidizing to most metals.

Where the requirements cannot be obtained with any form of open firing with combustion control, bright-annealing methods must be used. Much of the preceding discussion of mixing and ratio control applies to the control of fuel and air to the bright-annealing generators, since the atmosphere gas supplied by the generator depends upon the gas and air combination supplied for combustion in the generator.

# Chapter 4

## Heat Transfer and Fuel Economy

As the practical effect of heat transfer is principally important in its relation to fuel economy, it appears logical to include the two subjects in one chapter. Moreover, as heat transfer affects the determination of the size of a furnace, this subject is also discussed in this chapter. Methods of determining fuel consumption quickly but with sufficient accuracy for the selection of burners have already been discussed in Chapter 2, which involves a consideration of heat transfer and to some extent overlaps the discussion in this chapter.

The theoretical background of heat transfer as involved in industrial furnaces is an extremely extensive subject which has filled many books, and it is not the purpose of this book more than to mention it. The practical results from this theory are summarized and presented as an aid in solving many of the problems which arise in connection with the design and operation of heating furnaces. Also, the detailed calculation of fuel requirements is not a part of this volume; but practical figures on fuel economy in many different kinds of steel mill furnaces are presented as a guide of sufficient accuracy for most practical purposes.

### Heat Transfer in Industrial Furnaces

The various methods of heat transfer in furnaces includes:

(1) Conduction: within the steel, from liquid baths to steel, through refractory linings, etc.
(2) Radiation: between flame, refractories, and heated steel, and through openings in the furnace to the outside.
(3) Convection: between gases in contact with refractories and heated steel.

All three of these transfer mechanisms are simultaneously involved in any heating furnace and, as has already been stated, the mathematical and theoretical derivation is exceedingly complicated. The familiar Stefan-Boltzmann law is based upon the difference of the fourth powers of the absolute temperatures, and is the basis for the calculation of radiation values. Some form of equation involving simple difference between temperatures is usually the basis for calculation of transfer by convection and conduction. However, the use of any of the mathematical formulas

involves the assumption of coefficients, flame and wall temperatures, and other factors practically impossible to calculate, and it is in these assumptions that the mathematical methods usually fail. Theoretical research is essential, but in this case only as a means of understanding and using empirical data.

**Heating of Steel Shapes.** For a most complete and authoritative study of both the mathematical and experimental determination of the heating of steel in different forms, the reader is referred to a series of articles by Mr. J. D. Keller.* The time required to heat the steel thoroughly is the important thing, and from these articles and from other references and tests the following data have been prepared.

For the heating of flat mild steel *plates* in a constant-temperature furnace with plates exposed to heat from both sides, Figure 86 has been taken from Keller's articles. The values are calculated using a coefficient of 60 per cent of "black body" radiation for usual conditions. For steel with a

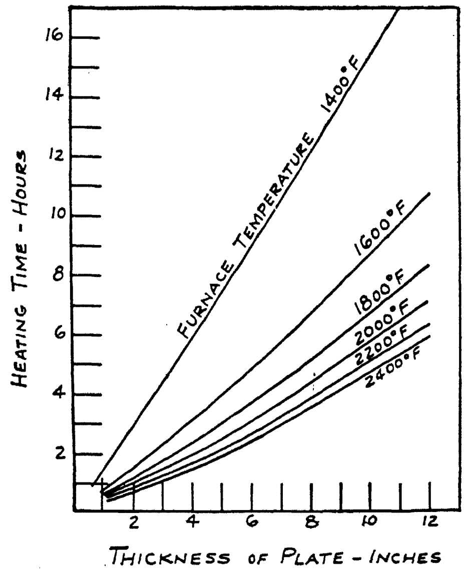



Figure 86. Time required for heating flat mild steel plates in constant temperature furnace. Plates exposed radiation from both sides.

bright-machined surface the times shown in the illustration might increase as much as 50 per cent. The values in this illustration are based upon a difference of $\frac{1}{2}$ per cent between furnace and final steel temperature and also upon a final temperature variation in all parts of the heated plate of less than $\frac{1}{2}$ per cent of the furnace temperature, which can be considered as a very good heating with all necessary soaking at temperature.

Figure 87 is for *rounds* when exposed to heat from all sides. The coeffi-

* Keller, J. D., *Heat Treating and Forging* (Nov. and Dec. 1933, Oct. and Dec. 1934, Feb. 1935).

cient is again 60 per cent of "black body," and the application of heat is assumed to be uniform. For rounds which are shorter than three times the diameter the heating time will be less than that shown on the curve. For *square bars* exposed to heat on all sides, the time to heat is just one-

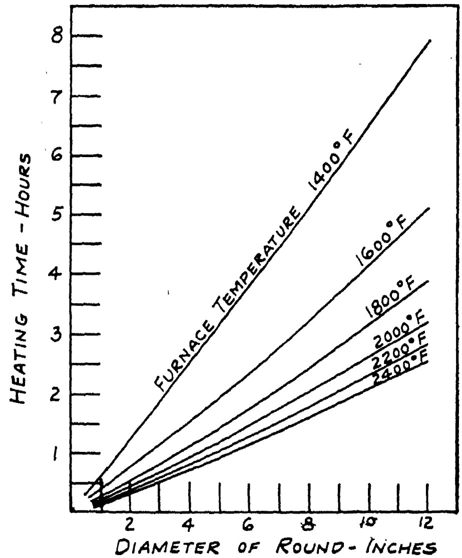



Figure 87. Time required for heating mild steel rounds in constant-temperature furnace. Cylinders long in proportion to their diameter and exposed to radiation from all sides. Radiation absorption coefficient taken as 60 per cent of black body coefficient.

half of that required for plates of the same thickness heated from both sides. Therefore, the time for square bars may be obtained directly from Figure 86 for plates by reading the time for the same thickness and furnace temperature and dividing this result by 2.0.

An idea of the heating time for *cubes* of steel may be gained from the fact that the time to heat an 18-in cube thoroughly in a furnace at 1600 deg F is 4.0 hours.

The heating time for *round ingots* to 2300 deg F is about 4.0 hours for 20-in diameter and 8.5 hours for 40-in.

*Thin sheets* heat very rapidly in separate pieces or in strands, as do *wires*, and both are very sensitive to furnace temperature. For example, a wire of 0.150-in diameter will heat thoroughly in 2 minutes in a furnace at 1900 deg F; but if the furnace temperature is increased to 2300 deg F the same temperature may be obtained in one minute, or one-half the time. In the heating of *sheets in piles* the conduction of heat is very much less in a direction perpendicular to the sheets than it is along the sheets. One careful investigation in Germany has shown the conduction along the sheets to be 3.5 times as great as it is in a direction across or through the sheets.

A careful test on the heating and cooling of an individual *coil of strip* steel $5\frac{1}{4}$ in wide $\times$ 0.040 in thick and weighing 850 lbs has shown that

thorough heating to 1350 deg F throughout can be accomplished in 5.25 hours (the outside reached temperature in 4.25 hours). After soaking at this temperature and placing in still air, all parts of the coil will cool to 200 deg F in 6.5 hours. The same coil, when part of a load of 5000 pounds in a circular retort furnace, will require as much as 25 hours to reach temperature throughout, demonstrating the limitations of the furnace to supply heat in such a case (as contrasted with the ability of the coil to absorb heat); cooling will also be much slower in such a mass.

The time required to heat materials is inversely proportional to the diffusivity of the material, which is the expression: $\frac{\text{Conductivity}}{\text{specific heat} \times \text{density}}$ This factor for common metals is given in the following tabulation:

Table 26. Diffusivity of Common Metals

| Metal | Conductivity (Btu/sq ft/hr/deg F/ft thickness) | Specific heat (Btu/lb/deg F) | Density (lb/cu ft) | Diffusiv |
|---|---|---|---|---|
| Mild steel | 34.0 | 0.165 | 488 | 0.42 |
| Stainless 304 | 12.5 | .120 | 495 | .21 |
| Stainless 410 | 15.3 | .160 | 485 | .20 |
| Alloy tool steel | 26.0 | .175 | 481 | .31 |
| Nickel | 33.0 | .108 | 549 | .56 |
| Cast iron | 28.0 | .110 | 450 | .56 |
| Copper | 212.0 | .104 | 555 | 3.67 |
| Brass | 63.0 | .100 | 530 | 1.19 |
| Aluminum | 116.0 | .247 | 165 | 2.85 |

From this table it is evident that the heating time compared with mild steel will be about twice as long for stainless steel and about one-half as long for brass. The relative heating time indicated by the diffusivity for copper and for aluminum will not hold in practice, because of the inability of the reflecting surfaces of these metals to absorb heat at the indicated rates.

The recently advertised method of high-speed heating in confined space with high temperature differences (sometimes referred to as patterned combustion, "hell-hole" heating) represents an adaption of old principles rather than of new laws, and has been limited in application to special heating cases. The advantage is minimum surface damage from short time of exposure to heat, and the disadvantages include higher fuel consumption, and uneven or over-heating if the time is not very accurately controlled. A variation of this method is used in the heating of billets in two separate furnaces, one for preheating and one for high-speed finishing to final temperature in a small furnace with high temperature head.

**Heating of Refractories.** The subject of heat flow through furnace *walls* of various refractory combinations has been discussed at considerable length in Chapter 3. These combinations did not include "light refractories"

(insulating firebricks) which have rapidly become of major importance in any discussion of refractories, and should be described and evaluated at this point.

These bricks were developed to reduce the time required to heat a furnace from cold to operating temperature and to reduce the heat storage loss in the furnace lining. Because of their light weight they were quickly adopted for hood-type movable furnaces and soon proved to be an interesting and important development. They are now widely used in all kinds of furnaces, especially those used for heat-treating.

The majority of insulating refractories are made from fireclay materials and depend for their insulating properties on the porosity which is imparted in their manufacture. The weight of a standard 9-in brick varies from about 1.5 to 2.5 lbs, as compared to about 8 lbs for the usual firebrick. The bricks in this class are designed to be exposed directly to the furnace atmosphere, but several different grades are made for different furnace temperatures (usually 1600, 2000, 2300, 2600, and 3000 deg F). Since the insulating value tends to vary directly with the porosity, and since the porosity must be lowered for resistance to higher temperature, it follows that the grades for higher temperatures have a lower insulating value, greater weight, and greater heat storage losses than those designed for lower temperatures.

Furnaces lined with insulating refractories heat and cool much more rapidly than those with the usual firebrick lining and save their initial cost in a short time on intermittent operation. On this kind of operation, the speed of heating is from two to three times as fast when lined with light bricks designed for operation under 2000 deg F.

The following tabulation gives some of the more important characteristics of typical insulating refractories for various maximum temperatures, as compared to those for a typical firebrick.

Table 27. Properties of Refractories

| | Insulating firebrick | | | | Firebric |
|---|---|---|---|---|---|
| Maximum temperature (deg F) | 1600 | 2000 | 2300 | 2600 | 2800 |
| Weight of 9 in brick (lbs) | 1.0/2.0 | 1.5/2.0 | 2.0/3.0 | 2.0/3.0 | 8.0 |
| Average lbs per cu ft | 24 | 34 | 45 | 45 | 130 |
| Conductivity at 1200 deg F (Btu/sq ft/hr/deg F/inch thick) | 1.4 | 2.0 | 2.5 | 2.7 | 9.0 |
| Specific heat | .25 | .25 | .25 | .25 | .26 |
| Cold crushing strength (lbs per sq in) | 100/200 | 100/300 | 150/450 | 150/450 | 900 |

The heat flow through *furnace hearths* has been studied by J. D. Keller * and his conclusions cover the subject with admirable completeness and clarity. A summary of these conclusions is as follows:

* Keller, J. D., "The Flow of Heat through Furnace Hearths," presented before the American Society of Mechanical Engineers (May 14, 1928).

"1. The total flow of heat through hearths of a given shape is proportional, not to the area but only to the diameter or width.
2. The equivalent thickness (thickness of a furnace wall having the same heat loss) of the hearth at its center is slightly more than one-half of the (inside) least width of the hearth.
3. The *average* equivalent thickness, referred to the whole area of the hearth, is 25 per cent of the hearth diameter for a circular furnace, 22.5 per cent of one side for a square hearth, and for rectangular hearths it increases as the length increases, approaching a limiting value of 27 per cent of the least width in the case of a very long hearth.
4. The total loss through a hearth, after steady temperature conditions have been reached, is

$$Q = \frac{SCA(T_i - T_o)}{D}$$

where $Q$ is the heat flow in Btu per hour through the hearth of area $A$ square feet, maintained at inside temperature $T_i$ when the temperature of the outside air is $T_o$. $C$ is the conductivity of the hearth and material beneath it in Btu per hour, deg F, square foot, and foot thickness, and $D$ is the diameter or least width of the hearth. $S$ is a shape factor of 4.00 for circular hearths, 4.40 for square hearths, and for rectangular hearths varying from the last named factor down to 3.73 for very long rectangles.
5. The rate of heat flow is least at the center, increases at distances farther from the center, and approaches an infinite value at the edge. As such a rate cannot, of course, be maintained, the parts of the hearth very close to the edge are necessarily colder than other parts of the furnace. The corners are still colder.
6. Of the total hearth loss, almost one-third escapes through the outermost 5 per cent of the hearth width.
7. Increasing the sidewall thickness reduces the loss through the hearth, affecting chiefly the outer 5 per cent referred to above.
8. The temperature penetration into the ground may be found from the expression:

$$T = T_o + (T_i - T_o)e^{-1.92\,z/D}$$

$T$ being the temperature at depth $z$ below the center of the hearth surface.
9. In a 2200 deg F furnace, if protecting the concrete foundation requires that the latter shall not exceed 900 deg F, the firebrick thickness above the center of the concrete must be 48 per cent of the hearth diameter or width.
10. After lighting up a furnace, weeks and even months may elapse before the temperatures and rate of heat flow approach within even

10 or 20 per cent of the final values. The initial heat flow rate is very high, but drops rapidly at first, and then more slowly as steady state conditions are approached.

11. Insulating a hearth by placing a horizontal layer of the usual insulating material on top of the foundation is not very effective. The result could be much improved, in some furnaces, by proper design and the use of special materials.
12. The presence of water in the ground at relatively shallow depths below the surface and in considerable quantity, may not only greatly increase the heat loss but may even endanger the stability of the furnace."

While the formulas presented by Keller can be of value to the furnace engineer in certain instances, the most important value of his paper is to prove the necessity for an air space between the furnace hearth and the foundation. Most modern furnaces are built in this manner, using either structural beams or brick piers to provide this space.

**Heat Transfer within the Furnace.** It is true that the mathematical method can be applied to furnaces in which very small charges are heated to obtain accurate values of heating rate, but for most industrial furnaces the calculation becomes too complicated to be reliable. In the case of a small charge the rate of heating is controlled by radiation from wall to charge, while when the charge is larger the transfer from flame to wall is most important and most difficult to calculate.

The overall coefficient of heat transfer in a heating furnace is the sum of the coefficients of transfer by radiation and by convection. The coefficient of convection is usually considered as practically constant, between 2.0 and 3.0 Btu per sq ft per hour per deg F temperature difference, where the area is that of the receiving surface. The coefficient of transfer by radiation in furnaces with small charges varies with the temperature of the furnace and of the receiving surface. (Examples of the magnitude of this coefficient are 3.5 Btu per sq ft per hour per deg F temperature difference for a furnace at 1000 deg F and a charge at room temperature, and 55.0 for a furnace at 2200 deg F with charge at 2000 deg F.) As has previously been explained, these values do not apply in production furnaces with larger charges.

Trinks * has outlined values of overall coefficient for various conditions of flame luminosity and temperature, with reservations as to their practical application. These values show less variation of the coefficient with non-luminous than with luminous flames, as would be expected. The variation is from 6.0 to 8.0 Btu per sq ft per hour per deg F for non-luminous flames with steel temperatures from 1200 to 3200 deg F and gas temperatures in all cases 100 degrees higher than the final surface temperature of the steel.

* Trinks, W., "Industrial Furnaces," Vol. 1, John Wiley and Sons, New York.

The same values for luminous flames with 100 degrees final temperature head are 10.0 to 29.0 Btu for the same temperature range.

An interesting article * describes a series of experimental results similar to those to be described in the following discussion. All of these tests, however, fall in the class where the charge is small compared with the size of the furnace. The value of the overall coefficient found in these tests, when converted to English units, is about 10.8 Btu when heating steel to 840 deg F in a 960-degree furnace. The mean values for heating copper with 120 deg F final temperature head varied from 3.7 to 11.5 Btu with surface temperature variations from 390 to 1400 deg F. For aluminum with 120 degrees final head, the overall coefficient was 5.5 Btu when heating the aluminum to 840 deg F in a 960-degree furnace.

The purpose of the present discussion is to describe results derived from an investigation of the operation of a number of commercial furnaces by the author, to determine reliable experimental values of overall coefficient of heat transfer. Furnaces in which the charge is relatively large with respect to the furnace were studied, for this type of furnace is the usual production furnace and is the least understood.

A list of commercial furnaces was made, the operation of all of which was well known to the author and in which fairly complete temperature and production measurements had been made. In some instances, where tests were made before this study of heat transmission was contemplated, it was necessary to estimate some of the required data, but such estimates were used only where the knowledge of the probable values was considered to be reliable.

For each furnace, the rate of heating in pounds per sq ft per hour was first determined by dividing the production from the furnace by the inside area of the furnace hearth. The rate of heat absorption by the steel was then calculated by dividing the heat content at known temperature (Btu per hour) by the constant effective receiving area of the steel in the furnace (sq ft). This area was taken as the steel area in the furnace, which is so located that it is capable of receiving heat by radiation or convection. A subsequent example will clarify this interpretation.

The overall coefficient of heat transfer in Btu per sq ft of steel per hour per deg F temperature difference was then found by dividing the above rate of heat absorption by the difference between the mean temperature in the furnace and the mean temperature of the surface of the steel while in the furnace.

As an example of the method of calculation let us take furnace No. 3 in Table 28. In this furnace, steel billets $4\frac{1}{4}$ in square and 9 in long are pushed end to end in six rows in the grooves shown in Figure 88. The inside dimensions of the furnace are 4.5 ft wide $\times$ 20 ft long, so that the rate of heating

* Wagner, G., *Z. Metallkunde*, **24**, Part 2 (February, 1932).

with a production of 3420 lbs per hour is 38.0 lbs per sq ft of hearth per hour. The final temperature of the steel was 2240 deg F, at which temperature the heat content is 350 Btu per lb.

The total area for all four sides of the billets in the six rows is $6 \times 4 \times 4\frac{1}{4} \times 240$ in long = 24,500 sq in, or 170 sq ft. An assumption is made at this point that the effective receiving area is 75 per cent for the position of

Figure 88. Groove hearth furnace for heating steel slugs.

the billets in the grooves shown in Figure 88. The absorbing area is then 75 per cent of 170 sq ft, or 127 sq ft. The rate of absorption is therefore

$$\frac{3420 \text{ lbs per hr} \times 350 \text{ Btu per lb}}{127 \text{ sq ft}} = 9450 \text{ Btu/sq ft/hr}$$

The temperature in the furnace was 2300 deg F at the discharge end and the mean temperature through the length of the furnace was 2200 deg F. The mean temperature of the surface of the steel was 1440 deg F. The difference is 760 deg F and the overall coefficient of heat transfer is

$$\frac{9450 \text{ Btu/sq ft/hr}}{760 \text{ deg F}} = 12.4 \text{ Btu/sq ft/hr/deg F}$$

Table 28 gives the complete data and calculated results for the furnaces which were studied. In all the furnaces in this table the steel was charged cold. The effect of preheated steel is discussed later. In most of these furnaces the total area of the steel in the furnace could be used in calculating the heat absorption, because the material was conveyed or supported so that each piece was exposed to the heat on all sides. Correction for effective

area was made where necessary, however, as in the continuous forging- and rolling-mill furnaces, where the pieces were pushed side by side and only the top and bottom of each piece were effective. In furnace No. 9 the sheets were held several inches off the bottom to permit circulation, but only 75 per cent of the area of both sides was considered effective to allow for difference in radiation to the two sides.

Figure 89 was prepared to show the relation between the rate of heating and the overall coefficient for the examples in Table 28. When the points, numbered the same as in the table, are plotted, they show that a consistent

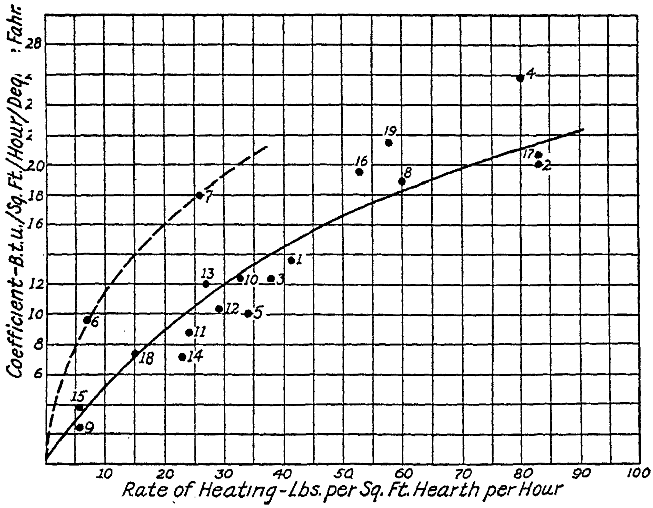



Figure 89. The overall coefficient of heat transfer increases with the number of pounds of steel heated on each square foot of hearth every hour.

relation exists between the rate of heating and the coefficient, and the solid curve was drawn to represent this relation. Examination of the points which depart widely from this curve indicates the reason for the discrepancies.

No. 4 furnace is a forging furnace fired by means of the so-called luminous or radiant burners, and supports the claim that the rate of heat transfer is increased by this type of combustion. Furnace No. 6 is for a large charge of 53 tons of steel heated for 35 hours in the furnace and No. 7 is also for a large charge of 17 tons heated for 23 hours. In both cases this large weight is made up of very few pieces (one piece in example No. 7) and the tentative curve shown by a dotted line is given to show the apparent relation for this rather unusual class of furnace operation, involving the very slow heating of large pieces. The explanation of the high values for overall coefficient probably lies in the fact that the temperature difference between the furnace and the surface of the steel is small for a long period

Table 28. Complete Data and Calculated Results for Furnaces Studied

| No. of furnace | Fuel utilized | Purpose of furnace | Product heated | Type of furnace | Furnace temperature (deg F) | Rate of heating (lbs/sq ft/hr) | Overall coefficient (Btu/sq ft/hr/deg F) |
|---|---|---|---|---|---|---|---|
| 1 | Oil | Forging | $2\frac{1}{2} \times 2\frac{1}{2}$-in billets | Pusher | 2400 | 41.6 | 13.6 |
| 2 | Oil | Forging | $2\frac{1}{2} \times 2\frac{1}{2}$-in billets | Pusher | 2500 | 83.0 | 20.7 |
| 3 | Natural gas | Forging | $4\frac{1}{4} \times 4\frac{1}{4}$-in billets | Pusher | 2300 | 38.0 | 12.4 |
| 4 | Coke oven gas * | Forging | 2-in diameter bars | Batch | 2300 | 80.0 | 25.8 |
| 5 | Oil | Rolling | $4 \times 4$-in billets | Batch | 2200 | 33.7 | 10.0 |
| 6 | Natural gas | Annealing | 20-in diameter rolls | Car | 1750 | 6.9 | 9.6 |
| 7 | Oil | Forging | 44-in diameter ingots | Batch | 2350 | 26.0 | 18.0 |
| 8 | Oil | Forging | $10 \times 4\frac{1}{2} \times 2\frac{1}{2}$-in bars | Rotary | 2400 | 60.0 | 18.9 |
| 9 | Natural gas | Normalizing | Stainless steel sheets | Rotary | 2040 | 5.8 | 2.4 |
| 10 | Electricity | Hardening | Rollers in pans | Pusher | 1550 | 32.7 | 12.4 |
| 11 | Oil | Hardening | Axles | Pusher | 1400 | 24.2 | 8.7 |
| 12 | Natural gas | Normalizing | Axles | Walking beam | 1650 | 29.3 | 10.3 |
| 13 | Oil | Drawing | Axles | Pusher | 1060 | 27.0 | 12.0 |
| 14 | Natural gas | Drawing | Axles | Walking beam | 825 | 23.5 | 7.1 |
| 15 | Natural gas | Annealing | 20-in diameter retorts | Car | 1380 | 5.9 | 3.8 |
| 16 | Natural gas | Normalizing | Strip steel | Chain | 2000 | 53.3 | 19.5 |
| 17 | Electricity | Normalizing | Strip steel | Roller | 2100 | 83.3 | 20.5 |
| 18 | Natural gas | Normalizing | $9\frac{5}{8}$-in diameter pipe | Sloping hearth | 1750 | 15.2 | 7.3 |
| 19 | Producer gas | Rolling | $12 \times 12$-in blooms | Pusher | 2200 | 58.0 | 21.5 |

* This furnace was fired with radiant flame burners.

of time while the interior of the steel is coming to temperature. The mean temperature difference therefore, is comparatively low, with high coefficients obtained when this difference is divided into the heat absorption value.

The effect of the temperature and of the ratio of *wall area to stock area* on the coefficient of heat transfer has been discussed by other writers on the subject. Figure 90 has been prepared to show the effects of these factors for the examples of Table 28.

The respective values for the coefficient plotted against final furnace temperature are shown by the small black dots in Figure 90. It will be

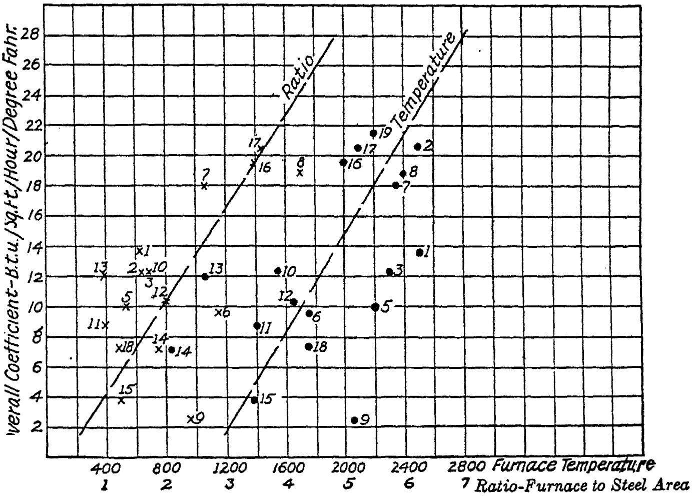



Figure 90. The overall coefficient of heat transfer increases rapidly with furnace temperature, and when the area of the furnace walls is greater than the area of the heated steel.

seen that these points indicate a definite increase of coefficient with furnace temperature, although the points are rather widely distributed and no very definite relation is established.

The effect of the ratio of interior refractory area of furnace to heat-absorbing area of the steel on the overall coefficient is shown by the crosses in Figure 90. Again there is a definite increase in coefficient with increase in the value of this ratio, but the points are again not in a definite straight-line relationship. The data for this relation are given in Table 29.

At this point it is interesting to examine the relation between mean temperature head and the rate of heating. Points 1 and 2 on the curve of Figure 89 are for the same furnace operated at different rates, and indicate that the relation between rate of heating and the coefficient is about the same for an individual furnace at different rates as it is for all ordinary commercial furnaces at various rates.

Table 29. Relation of Furnace-Stock Ratio to Coefficient

| No. of furnace | Area (sq ft) Wall | Stock | Ratio | Co-efficient |
|---|---|---|---|---|
| 1 | 273 | 175 | 1.56 | 13.6 |
| 3 | 206 | 127 | 1.62 | 12.4 |
| 5 | 255 | 197 | 1.30 | 10.0 |
| 6 | 1646 | 572 | 2.88 | 9.6 |
| 7 | 345 | 130 | 2.65 | 18.0 |
| 8 | 171 | 40 | 4.26 | 18.9 |
| 9 | 1296 | 540 | 2.40 | 2.4 |
| 10 | 86 | 52 | 1.66 | 12.4 |
| 11 | 454 | 459 | 0.99 | 8.7 |
| 12 | 228 | 114 | 2.00 | 10.3 |
| 13 | 454 | 470 | 0.97 | 12.0 |
| 14 | 260 | 140 | 1.86 | 7.1 |
| 15 | 890 | 708 | 1.26 | 3.8 |
| 16 | 285 | 81 | 3.53 | 19.5 |
| 17 | 108 | 30 | 3.60 | 20.5 |
| 18 | 3422 | 2880 | 1.19 | 7.3 |

If this statement is correct, then for any furnace it is possible to show the relation between the mean temperature difference, or temperature head, and the rate of heating, because the hearth area and the effective heat-absorbing areas remain constant in a given furnace. Therefore, the heat absorption per sq ft of steel varies directly with the rate of heating. By

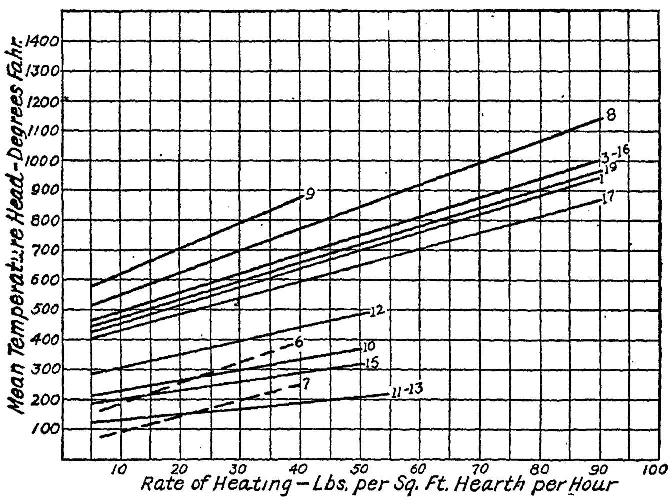



Figure 91. The mean temperature difference between furnace and heated material must be increased to increase the amount of material heated in a furnace.

dividing the heat absorption at several rates by the values of the coefficient from Figure 89 for the same rates, the mean temperature head for these rates is determined. Figure 91 shows this relation worked out for some of the examples of Table 28.

This illustration shows the mean temperature head; its practical application, including the determination of final temperature head, will be discussed later. It will be seen that the magnitude of the temperature head varies for the different types of furnaces, but that the effect of rate of heating on the head is the same for all types. This is to be expected with all the curves based upon the use of the same relation between coefficient and rate, as given in Figure 89.

Heating of steel which is already partially heated is a requirement of many furnace installations, and is a condition under which it is particularly difficult to predict the temperature head required. Examples of this type of heating are the annealing of forgings before they cool, reheating of billets, etc. Reliable examples in sufficient number for definite conclusions are not

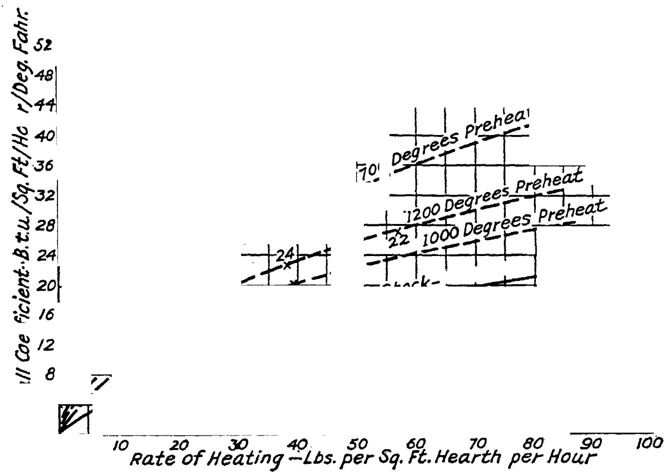



Figure 92. Dotted lines show that the overall coefficient of heat transfer is greater when hot material is charged into a furnace than when the material is heated from cold.

available, but a few with which the author is familiar have been worked out to give a tentative idea of the effect of preheated stock. Data for these examples are given in Table 30. These examples have been plotted in Figure 92 to show the relation between overall coefficient and the rate of heating, and the curve of Figure 89 for cold stock has been reproduced to show the comparison.

In the calculation of the overall coefficient the same method was employed as for the cold material, except that the heat content of the steel at the entering temperature was deducted from the heat content for the final temperature in calculating the heat absorption per sq ft of stock. The mean temperatures of the steel surface were naturally higher than for cold stock.

The curves of Figure 92 show that the preheating of the stock raises the coefficient above that for cold stock for the same rate of heating, in lbs per sq ft of hearth per hour. In view of the small number of points available the curves have been drawn in dotted lines to show the apparent relations for different values of preheat.

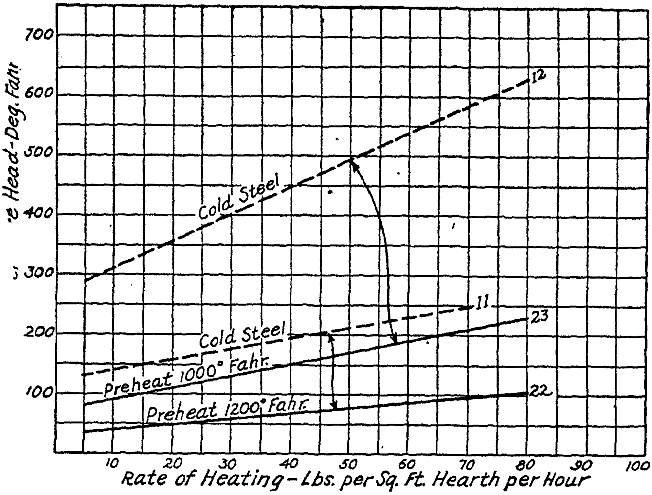



Figure 93. Comparison of dotted lines and solid lines shows the difference in temperature head required between pre-heated steel and cold steel entering the furnace, other conditions being the same.

Using the relations of Figure 92, it is again possible to calculate the mean temperature heads at the different rates of heating for the examples of Table 30 and the result is given in the two solid lines of Figure 93 for examples 22 and 23.

Table 30. Effect of Preheated Stock on Overall Coefficient

| No of furnace | Fuel utilized | Purpose of furnace | Product heated | Type of furnace | Temperature (deg F) Furnace | Preheat | Rate of heating (lbs/sq ft/hr) | Overall coefficient (Btu/sq ft/hr/deg F) |
|---|---|---|---|---|---|---|---|---|
| 20 | Electricity | Annealing | Steel disks | Roller | 1550 | 1000 | 39.2 | 20.5 |
| 21 | Electricity | Reheating | Forgings | Batch | 2450 | 1750 | 81.8 | 42.8 |
| 22 | Oil | Normalizing | Cranks | Pusher | 1650 | 1200 | 57.0 | 27.4 |
| 23 | Natural gas | Hardening | Axles | Walking beam | 1600 | 1000 | 38.2 | 22.7 |

The dotted lines of the illustration show tne curves for examples 11 and 12 from Figure 91. The furnaces for examples 12, for cold stock, and 23, for 1000 deg F preheat, were installed in line and of identical design with the same axles passing through them to be first normalized, then cooled to 1000 deg F between furnaces, and finally heated for hardening. A long thermocouple was run continuously through the two furnaces, so that an

extremely reliable idea of the effect of preheating is available from a study of these curves, which are connected by arrows in the illustration. The furnaces of example 11 for cold stock and 22 for 1200 deg F preheat were not in the same plant, but were furnaces of the same design heating a similar product.

The curves of Figure 93 indicate that the mean temperature head required to heat stock which has been preheated to 1000 deg F varies from 29 per cent of that required for cold stock at a rate of 10 lbs per sq ft per hour to 35 per cent of that for cold stock at a rate of 60 lbs. Similarly, the mean head for heating steel from 1200 deg F initial temperature varies from 28 per cent of that for cold steel to 37 per cent for the same rates of heating. These values indicate a discrepancy in the data, since the percentage for 1200 degrees of preheat should be somewhat smaller than for 1000 degrees; but the agreement for these two widely separated examples does prove that the relations established are at least approximately correct.

The comparisons between 1000 deg of preheat and cold steel are probably more correct than those for 1200 deg of preheat, because the conditions for the test in that case were ideal for comparison. More investigation is needed, however, on the subject of preheated steel.

Knowledge of the final temperature head is often of more importance to metallurgists than that of the mean temperature head in a furnace. By "final temperature head" is meant the difference in the temperature of the furnace at the point where the steel is discharged and the surface temperature of the steel when it leaves the furnace.

To establish a relation between the final temperature head and the mean head, Table 31 was prepared to show the value of the two temperature

Table 31. Relation of Mean Head to Final Head

| No of furnace | Mean temperature head (deg F) | Final temperature head (deg F) | Ratio: mean head to final head | Rate of heating (lbs/sq ft/hr) |
|---|---|---|---|---|
| 1 | 650 | 80 | 8.2 | 41.6 |
| 3 | 780 | 67 | 10.1 | 38.0 |
| 5 | 780 | 70 | 11.1 | 33.7 |
| 8 | 900 | 150 | 6.0 | 60.0 |
| 9 | 600 | 70 | 8.6 | 5.8 |
| 11 | 160 | 17 | 9.6 | 24.2 |
| 13 | 144 | 20 | 7.2 | 27.0 |
| 14 | 190 | 20 | 9.5 | 23.5 |
| 15 | 157 | 25 | 6.3 | 5.9 |
| 16 | 680 | 325 | 2.1 | 53.3 |
| 17 | 880 | 400 | 2.2 | 83.3 |
| 18 | 290 | 50 | 5.8 | 15.2 |
| 20 | 150 | 20 | 7.5 | 39.2 |
| 21 | 170 | 85 | 2.0 | 81.8 |
| 22 | 85 | 30 | 2.8 | 57.0 |
| 23 | 130 | 25 | 5.2 | 38.2 |

heads for the majority of the examples of Table 28. From the information in this table, Figure 94 was prepared to show the graphical relation between the ratios of mean head to final head and the rate of heating in the furnace. The points marked by black dots are for cold steel and those indicated by crosses are for the preheated examples of Table 30.

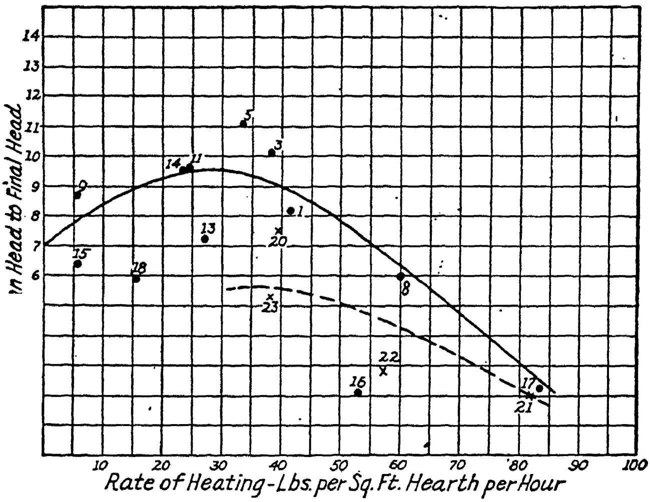



Figure 94. The final temperature head in a furnace is greatest with respect to the mean temperature head when the production varies either above or below the usual heating rates.

It is evident that there are not sufficient points available to establish a definite relation, particularly in the case of preheated stock, but the two tentative curves have been drawn to represent the apparent relation for cold and preheated steel, based upon the points available.

It will be seen that lower values of the ratio are indicated for both low and high rates of heating than for the more usual rates of furnace operation. This appears to be entirely logical, since the fact that the surface of the steel is up to temperature for a long period of time at low rates of heating causes the mean head to be relatively low, while at high rates the final head is relatively high.

The curves of Figure 94 will serve to indicate the approximate final head to be expected at any given rate of firing for usual types of furnaces, not including those heated by luminous flame burners or those in which the pieces to be heated are unusually large with very long heating cycles.

As an example of the use of the data which has been given to determine temperature heads, suppose that 10,000 pounds of steel pipe are to be heated in a furnace 25 feet wide and 13 ft long to 1700 deg F for normalizing. The

pipes are $\frac{7}{8}$ in outside diameter and 23 feet long, and are carried through the furnace on hot chains. Then, to determine the temperature head:

$$\text{Rate of heating is } \frac{10{,}000 \text{ lbs}}{25 \text{ ft} \times 13 \text{ ft}} \text{ or } 30.8 \text{ lbs/sq ft/hr}$$

From Figure 89 the overall coefficient of heat transfer at this rate of heating is 12.1 Btu per sq ft per hour per deg F.

On $1\frac{1}{2}$-in centers, 104 pipes will be in the furnace and the surface area of each pipe is 5.28 sq ft, so that the total area of the receiving surface is $104 \times 5.28 = 550$ sq ft.

The heat content per pound of steel at 1700 deg F above 60 deg is 250 Btu, so that the total heat absorbed is $10{,}000 \times 250 = 2{,}500{,}000$ Btu per hour. Then,

$$\begin{aligned} \text{Let} \quad H &= \text{mean temperature head, and} \\ 12.1 \times 550 \text{ sq ft} \times H &= 2{,}500{,}000 \text{ Btu/hr, and} \\ H &= 375 \text{ deg F} \end{aligned}$$

Using the values of Figure 94, the ratio of mean temperature head to final head at a rate of 30.8 lbs per sq ft of hearth per hour is 9.4, so that the final head in this case will be $\frac{375}{9.4} = 40$ deg F.

**Recirculation, or Forced Convection Furnaces.** This type of furnace, which was discussed briefly in Chapter 3, has increased rapidly in popularity for temperatures below about 1300 deg F because of the rapid heating and uniform temperature possible with this method. The principle involved is that the transfer of heat by convection can be increased by increasing the velocity of the furnace gases.

The percentage of heat transferred in a furnace by convection (the remainder is transferred by radiation) is about as follows:

| Furnace temperature (deg F) | % of total heat transferred by convection |
|---|---|
| 200 | 50 |
| 400 | 34 |
| 600 | 25 |
| 800 | 20 |
| 1000 | 17 |
| 1200 | 14 |
| 1400 | 13 |
| 1600 | 12 |
| 1800 | 11 |

Forced convection furnaces have been built for temperatures up to 1800 deg F, but an examination of this tabulation will point out the fact that the application is questionable for temperatures above 1300 or 1400 deg F. The construction is considerably more expansive, and the benefits are limited to an improvement in the heat transfer by convection,

which comprises less than 14 per cent of the total at temperatures above 1200 deg F.

The formula for the heat transfer coefficient in convection heating is

$$C = 1.0 + 2.7 \times \text{density of gas} \times \text{velocity of hot gas, (ft/sec)}$$

or, in other words, the coefficient of heat transfer varies almost directly with the velocity of the gases in the furnace. Therefore, by increasing this velocity, the speed of heating and the uniformity of temperature within the furnace can be increased.

A considerable increase is accomplished by the simple expedient of a fan in electric or fuel-fired furnaces, but the usual method is to use fuel-fired recirculation units, which consist of burner, combustion chamber,

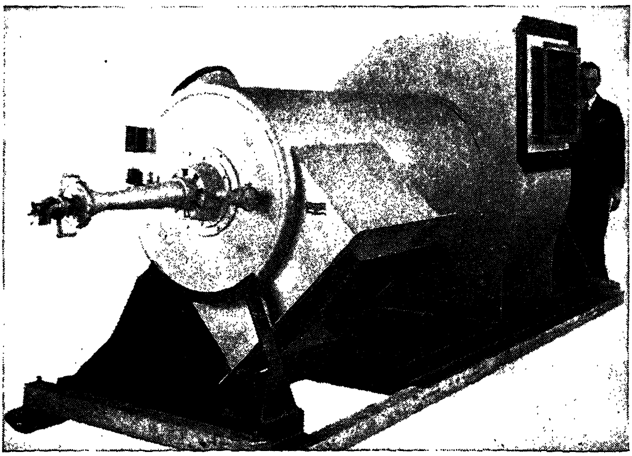


Figure 95. Recirculating heating unit with fan and combustion chamber.

and fan for hot gases. Materials are used which will withstand the temperature for which the unit is designed. Figure 95 shows a typical machine of this type.

The supply of gases from the unit is usually connected to the top of the furnace, with the gases leaving the furnace at the bottom and returning to the unit inlet. However, there are many variations, as in the case of the car type furnace of Figure 96, where the hot gases enter the furnace at one side and leave at the opposite side. Air is mixed with the products of combustion from the burner and the mixture circulates through the furnace and the unit. The gas vented from the furnace or lost through the openings is just equal to the amount introduced at the burner. The temperature drop of the recirculated gases in the furnace will depend upon the amount circulated, and should not exceed 50 deg F under soaking conditions for good uniformity of temperature. For this condition in a

furnace at 1000 deg F it is necessary to circulate about 12,000 cfm (hot measure at operating temperature) per million Btu per hour input to the heater unit (rating of the unit). For example, with a unit rated at 2,000,000 Btu per hour, the circulation should be about 24,000 cfm, which in an average furnace served by such a unit will correspond to about 25 to 30 atmosphere changes per minute. Under these conditions the total temperature variation in any part of the furnace will not exceed ± 10 deg F variation with proper arrangement of the ducts.

The use of insulating refractories is desirable, if not essential, in this type of furnace, because a saving in heat input required has a great effect on the size and cost of the recirculating unit.

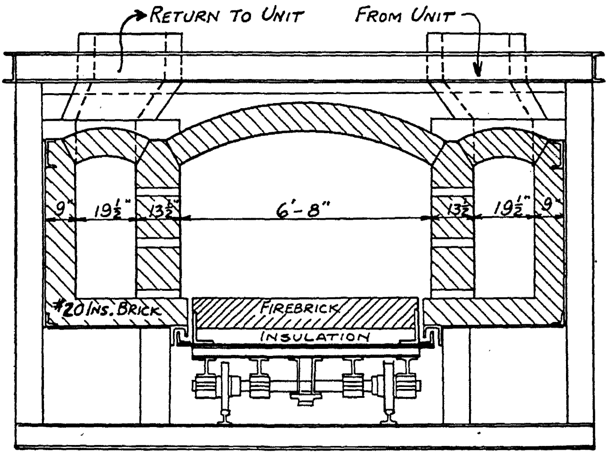



Figure 96. Recirculation — fired car furnace utilizing unit of Figure 95.

Automatic temperature control is usually applied to the gas entering the furnace, with pyrometers in the heating chamber of the furnace to indicate or record the temperature. On large furnaces several recirculating units may be used, each comprising a separate zone of temperature control.

## Size of Furnaces

A summary of the factors which affect the size of a furnace for given requirements includes:

(1) The amount of steel to be heated per hour to a given temperature.
(2) The physical dimensions of the pieces to be heated and the amount of soaking time (after thorough heating) necessary for the desired treatment.
(3) The allowable rate of heating in the furnace (lbs of steel per sq ft of furnace hearth per hour).

The amount of steel heated per hour involves the regularity of production and the method of handling (batch, continuous, etc.), and it is essential to know the maximum and minimum weights per hour and the probable percentage of time at each rate in order to arrive at the average weight in pounds per hour. Furnaces which are too small have a short life and produce poor heating results, while those which are too large are wasteful in fuel; thus careful investigation of the rates of production is desirable.

The heating time of steel pieces of various shapes has been discussed in this chapter and the metallurgical requirements for soaking after reaching temperature must be supplied by the metallurgist. Knowing the weight of steel per hour and the weight of each piece, the number of pieces per hour is easily determined. Then from the total heating time the number of pieces which must be in the furnace at any one time is determined by multiplication. Knowing the size of the pieces and the number which may be piled without distortion or interference with heating, the hearth area required on this basis may be calculated.

The calculation to this point has been based entirely on the ability of the steel to absorb heat (conduction within the steel) and the hearth area so obtained must be checked by consideration of the third factor (allowable rate of heating in lbs per sq ft of hearth per hour) which takes into account the brick area available for radiation, the rates of heat transmission already discussed in this chapter, and other factors. This allowable rate varies for different kinds of furnaces, and a good idea of the variation may be obtained from Table 33. In some cases, as when heating ring gears for quenching, the hearth must be determined from the individual pieces with resulting heating rates under 10 lbs per sq ft of hearth per hour, while for the quenching of most shapes (shafts, bolts, springs, etc.) in continuous furnaces a rate between 25 and 30 lbs per sq ft of hearth per hour is allowable.

As an example of the calculation of furnace size, suppose that it is required to heat steel pieces $6 \times 6 \times 18$ in long weighing 200 lbs each to 2200 deg F for forging, and that it has been decided that the pieces will be pushed end to end through grooves in the hearth of a continuous furnace. The production is to be 500 net tons per month, with 25 working turns of 8 hours each.

The average production per hour will be $\frac{500 \text{ tons} \times 2000 \text{ pounds}}{25 \text{ turns} \times 8 \text{ hours}} = 5000$ lbs.

This is the average figure for the month and it is probable that some days will be considerably larger than others in producing this average. The maximum day can frequently be determined from records, but in the absence of such information we shall assume that the average hourly rate for the maximum day in a month will be 6000 lbs.

Then $\frac{6000 \text{ lbs}}{200 \text{ lbs per piece}} = 30$ pieces per hour.

Assume that the heating time of these 6-in square pieces is 2 hours in the furnace. Then the furnace must contain $30 \times 2 = 60$ pieces at one time.

If the grooves are on 15-in centers, a convenient arrangement will be four grooves in a furnace 6 ft wide inside, and there will be 15 pieces in each row.

The effective length of the furnace will be 15 × 1.5 ft = 22.5 feet.

The effective hearth area of the furnace will be 6 ft × 22.5 ft = 135 sq ft.

The rate of heating will be $\frac{6000 \text{ lbs}}{135 \text{ sq ft}} = 44.4$ lbs per sq ft per hour.

This rate of heating is correct for the continuous heating of billets of this kind and verifies the assumption of two hours' heating time. For heating these same pieces in a batch, or in-and-out type of furnace, the allowable rate is only 25 lbs per sq ft per hour (on account of charging and discharging with some empty hearth at all times) and the required furnace hearth will be correspondingly larger for the same production.

## Fuel Economy

The fuel distribution in two typical steel plants producing about 600,000 tons of semi-finished and finished carbon and alloy steels per year is shown in Table 32. Such a plant comprises coke ovens, two blast furnaces, 10 to 12 open-hearth furnaces, blooming mill, finishing mills, and necessary heat-treating facilities, and produces ingots, blooms, bars, rods, and wire or tubes.

Table 32. Distribution of Heat in Steel Plant
(Millions of Btu per month)

| | Plant 1 | Plant 2 |
|---|---|---|
| Coal to coke plant | 1,414,000 | 1,506,400 |
| Coke to blast furnaces | 730,000 | 800,000 |
| Tar from coke plant | 80,580 | 90,330 |
| Coke oven gas to coke ovens | 97,650 | 86,250 |
| Coke oven gas for distribution | 165,100 | 201,300 |
| Purchased natural gas | 11,760 | 5,100 |
| Coal to producers in mills | 184,800 | 129,000 |
| Open hearth furnaces | | |
| coal (to producers) | 183,120 | 315,280 |
| tar | 61,540 | 36,800 |
| coke oven gas | 32,400 | 56,900 |
| iron mixer | 3,800 | 1,600 |
| general, ladles, etc. | 5,450 | 1,800 |
| Blooming mill soaking pits | 90,970 | 73,830 |
| Finishing mills | 112,418 | 82,000 |
| Sintering plant | 1,000 | 1,400 |
| Boilers | | |
| blast furnace gas | 226,800 | 297,800 |
| coal | 419,360 | 368,900 |
| Heat-treating furnaces | 10,000 | 32,250 |
| Miscellaneous | 50,180 | 47,000 |

This volume is primarily interested in the fuel used at the blooming mill, finishing mills, and for heat-treating. The many different furnaces involved are described in Chapter 8, and the following tabulation gives the average fuel economy for many of these furnaces.

Table 33. Fuel Economy of Steel Mill Furnaces

| Process | Furnace type | Usual temp. (deg F) | Average production rate (lbs/sq ft/hr) | Overall economy (millions Btu/net ton [2000 lbs]) |
|---|---|---|---|---|
| *Ingot heating* (Majority hot ingots) | | | | |
| | Regenerative | 2300 | — | 1.0–1.5 |
| | Direct fired recuperative | 2300 | — | 0.8–1.3 |
| *Heating for bars* | | | | |
| Billet heating | Pusher | 2300 | 50 | 1.4–3.5 |
| Billet heating | Batch or rotary | 2300 | 25 | 3.5–6.0 |
| Quenching | Batch or continuous | 1600 | 25 | 2.0–3.0 |
| Tempering | Batch or continuous | 1000 | 20 | 1.0–2.0 |
| Strain drawing | Batch | 1000 | 20 | 1.0–2.0 |
| Normalizing | Batch or continuous | 1700 | 25 | 2.0–3.0 |
| High anneal | Batch | 1550 | 4 | 2.0–5.0 |
| Low anneal | Batch | 1300 | 5 | 1.0–4.0 |
| Slow cooling | Pit | 1500 | — | 0.3–1.0 |
| *Heating for rods and wire* | | | | |
| Billet heating | Pusher | 2300 | 50 | 1.2–3.5 |
| Billet heating | Batch | 2300 | 25 | 3.5–5.0 |
| Normalizing | Retort | 1650 | — | 2.5–3.5 |
| Normalizing | Continuous | 1650 | 30 | 1.5–2.5 |
| Annealing | Retort | 1350 | — | 2.5–3.5 |
| Patenting | Continuous strand | 1650 | 10 | 2.0–2.5 |
| Rod baking | Ovens | 450 | — | 1.2–1.8 |
| Rod baking | Flash | 750 | — | 0.8–1.2 |
| Salt anneal | Pot | 1350 | — | 2.5–3.5 |
| Galvanizing | Continuous strand | 900 | — | 0.8–1.2 |
| Lead anneal | Continuous strand | 1350 | — | 1.5–2.5 |
| Tinning | Continuous strand | 450 | — | 0.3–0.7 |
| *Heating for pipes and tubes* | | | | |
| Billet heating | Continuous roll-down | 2300 | 40 | 2.0–3.0 |
| Billet heating | Batch | 2300 | 25 | 3.5–4.5 |
| Reheating tubes | Roll-down | 1900 | 50 | 1.2–1.6 |
| Upsetting | Batch | 2400 | — | 2.3–2.8 |
| Butt weld | Batch | 2650 | 90 | 3.5–4.5 |
| Butt weld | Continuous | 2900 | 100 | 2.5–3.5 |
| Lap weld | Batch | 2650 | 90 | 3.5–4.5 |
| Open anneal | Batch | 1350 | 20 | 1.0–2.0 |
| Bright anneal | Continuous | 1350 | 30 | 1.0–2.0 |
| Normalize | Continuous | 1650 | 25 | 1.5–2.5 |
| Galvanizing | Pot | 900 | — | 1.0–1.5 |
| *Heating for strip and sheets* | | | | |
| Slab heating | Batch regenerative | 2300 | 25 | 4.0–5.0 |
| Slab heating | Batch recuperative | 2300 | 25 | 3.5–4.5 |
| Slab heating | Pusher | 2300 | 70 | 1.2–2.0 |
| Sheet bar heating | Batch | 1600 | 25 | 2.0–2.5 |
| Sheet bar heating | Continuous | 1600 | 30 | 1.5–2.0 |
| Pack heating | Batch | 1400 | 25 | 1.8–2.2 per heat |
| Pack heating | Continuous | 1400 | 30 | 1.2–1.8 per heat |
| Annealing | Continuous open | 1600 | 15 net* | 2.5–3.5 |
| Annealing | Cast boxes | 1350 | 10 | 1.8–2.2 |
| Annealing | Hood-retort | 1350 | 20 | 1.2–1.8 |
| Normalizing | Continuous | 2000 | 15 net* | 3.2–3.8 |
| Galvanizing | Pot | 875 | — | 1.0–1.5 |

* Not including waster sheets

# Chapter 5

# The Quenching of Steel

The subject of the *methods* of quenching steel has been almost entirely neglected by technical writers, which is surprising in view of the importance of this step in the heat treatment of steel, and of the wide variety of methods employed in quenching steel in its many different forms. The purpose of this discussion is to assemble and describe some of these methods, with information on the theory involved and useful operating data.

The discussion begins with an outline of the theoretical considerations, which have been covered in detail in many metallurgical texts. This is followed by a review of the different media employed for quenching, quantities of coolant required, and equipment for cooling and circulating the coolant. Finally, typical installations will be described for batch quenching, continuous quenching, fixture quenching, flood quenching, and surface and differential hardening.

## The Theory of Quenching

The purpose of quenching steel after heating is to produce hardness or other physical characteristics. The degree of hardness depends upon the rate of heat extraction, or cooling rate, for any given steel analysis. In pieces of any considerable size, the difference in the cooling rates at the center and surface of the piece will cause wide variation in hardness at these points, which can be partially offset by the use of alloy steels with lower critical cooling rates.

Maximum hardness of steels is obtained when a completely martensitic structure is obtained by the quenching operation, and complete hardening is possible only when the structure has been converted throughout the section of the piece. This requires that the center of the piece must be cooled at a rate exceeding the critical cooling rate of the steel under consideration. Data on critical cooling rates for different steels are scarce, but information given by Howard Scott * provides a guide to the range of values involved. He quotes from two authorities as follows:

"For SAE 2330 steel, critical cooling rate is 32 deg C (58 deg F) per second.

* Scott, Howard, American Society for Metals (1933).

"For SAE 1030 steel, critical cooling rate is 500 deg C (900 deg F) per second."

Any competent discussion of the metallurgical effects of quenching must be left to metallurgists, but some of their findings may be repeated here for the benefit of the practical heat treater or equipment designer as follows:

(1) The critical cooling speeds quoted above from Scott are the approximate range of speeds required to produce maximum hardness in common steels. Intermediate speeds less than the critical range for any given steel will produce a lesser degree of hardness by reason of the formation of other structures in the steel.

(2) Critical cooling speeds vary with the steel composition as indicated above, and with the details of manufacture of the steel.

(3) Increase in the carbon content of carbon steels from 0.20 to 0.90 per cent lowers the critical cooling rate. Above 0.90 per cent the rate is increased slightly by increase in the carbon content.

(4) The addition of some alloys greatly affects the critical cooling rate. Most of these, including nickel, manganese, and molybdenum, lower the rate to a considerable degree. In the case of high-speed tool steels this effect is so pronounced that the steels will harden in air.

(5) The addition of alloys makes possible degrees of hardness penetration which cannot be obtained with carbon steels, and without cracking from stresses set up by too rapid cooling.

Although at first glance the quenching of steel seems to be a simple matter about which a wealth of information should be available, actually the opposite is the case. This is probably due to the difficulties in the paths which lead to the only two sources of information. These two sources are theoretical derivation by mathematics and experimental determination of values.

The mathematical evaluation of cooling rates in air or in liquids by the application of the equations of Fourier or others is beset with many difficulties and weakened by the necessity for many assumptions. All mathematical derivations depend, for instance, on a value for diffusivity, which is the factor: $\frac{\text{Conductivity}}{\text{specific heat} \times \text{density}}$, which is directly proportional to the rate of heating or cooling of the center of a piece of steel (Table 26). Unfortunately this value is different for steel structures prevailing above the critical temperatures from those prevailing at the lower temperatures, and few, if any, accurate data are available for the higher temperatures. This necessitates assumptions of questionable accuracy.

Another assumption involves the quenching power of the various coolants, which in turn depends upon the rate of circulation of the coolant and

upon other variables which cannot be accurately evaluated by formula. Many calculations also assume instantaneous cooling of the surface of the quenched piece, which causes discrepancies between the calculated and the experimental results.

The value of the mathematical derivation is more qualitative than quantitative; it lies in the determination of comparative values for masses of different sizes and shapes, relation between depth of penetration and time, and the relative importance of the various factors involved. As an example

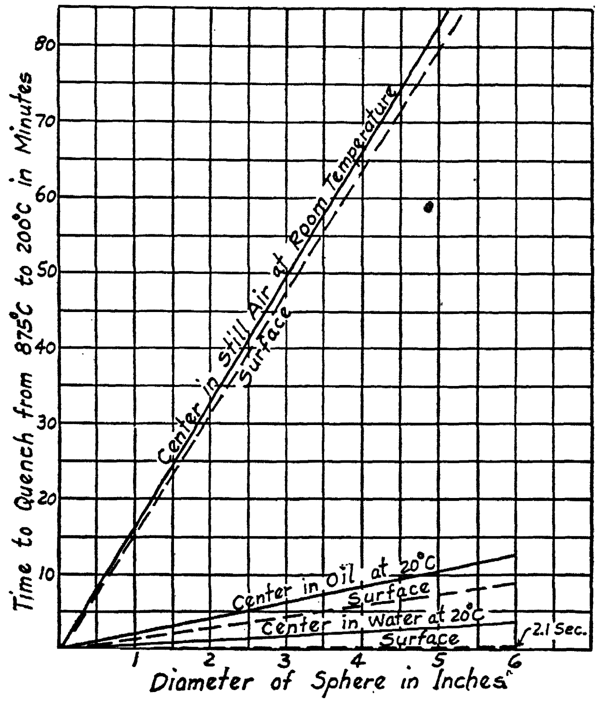



Figure 97. Experimentally determined comparative rates of cooling at the center and surface of various diameter spheres, when quenched in different media. (French)

of the useful application of mathematics, Scott gives the theoretical maximum rate of cooling at the center of a steel cylinder of given diffusivity as equal to $(70 \div D^2)$ deg C per second, where $D$ is the diameter of the cylinder in inches. A curve calculated from this relation is given in Figure 99 and the effect of diameter is clearly evident. The rate of quenching of a steel cylinder at the center as found by this formula is most nearly approached by quenching in agitated water, which is one of the most rapid practical methods of quenching available.

The experimental determinations of quenching data are more accurate, but are also complicated because of the many factors involved, including:

(1) Surface per unit of volume of the quenched piece.
(2) Size and shape of the piece.
(3) Temperature of the quenching medium.
(4) Temperature of the steel when quenched.
(5) Diffusivity of the steel.
(6) Surface condition of the steel.
(7) Liberation of gases in the bath.
(8) Method of introduction of the piece into the bath.
(9) Circulation or agitation of the coolant.

As has already been mentioned, the metallurgical effect of quenching involves the rate of cooling at both the center and surface of the piece; and these rates are widely different in most pieces. For example, French states that the *surface* cooling rate at 720 deg C (1300 deg F) in circulating water of spheres from $\frac{1}{2}$ to $11\frac{1}{4}$ in diameter is from 8000 to 1000 deg C (14,400 to 1800 deg F) per second. The relative rates of cooling at the center of spheres, long rounds, and large plates is 3 : 2 : 1, so that the rate for a sphere is about 50 per cent greater than for a long round of the same diameter. Using this relation and the formula from Scott already given, the calculated *center* cooling rate for spheres from $\frac{1}{2}$ to $11\frac{1}{4}$ in diameter is from about 420 to 1 deg C (756 to 2 deg F) per second. Figure 97 shows the experimentally determined comparative times of cooling at the center and surface of various diameter spheres when quenched in different media, as given by French.

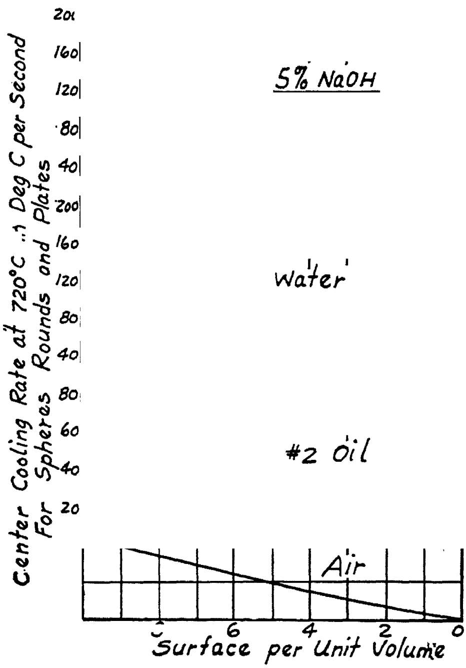
The rate of cooling of steel varies with the heating temperature, but the most important rate is that in the vicinity of the critical cooling rate, so that the rates given in Figure 98, as for most quenching data, are for the temperature range from about 600 to 750 deg C (1112 to 1382 deg F). After a rapid cooling rate through this temperature range it is desirable that the rate be as slow as possible below 400 deg C (752 deg F) to reduce cracking of the steel, which occurs during the hardening transformation. Fortunately, the typical cooling curve follows this general requirement, and further control is possible by the selection of the cooling medium or by automatic timing of the quenching mechanism, as is discussed later.

The *surface per unit of volume* is important because the quantity of heat to be lost is proportional to the volume, while the rate of removal depends upon the surface exposed to the coolant. The combination of volume and surface is therefore a better measure of the action on any piece of steel than is the surface or volume alone. Figure 98 illustrates the relation between surface per unit of volume and the rate of cooling at the center of spheres, rounds, or plates when cooled from 875 deg C (1607 deg F) with no agitation of the media. The rate of cooling at the center under given conditions will be the same for spheres, rounds, or plates with equal surface

per unit of volume. It has been determined experimentally that this is true, and the condition exists when the ratio of diameter of sphere, diameter of round of infinite length, and thickness of plate of infinite length and width is 3 : 2 : 1, respectively.

Useful information relating to *size and shape* is available in the curves of Figure 99. These curves include the maximum calculated theoretical rate of center cooling already discussed, and show the comparative cooling rate for rounds of different diameters when cooled in several common media.

Figure 98. Relation between surface per unit volume and rate of cooling at the center of spheres, rounds, or plates when cooled from 875 deg C.




With further regard to size it is recognized that the size may be so great that the surface per unit of volume is a small value. Under such conditions, the quenching rate is a function of the conductivity of the metal. The quenching of pieces of such magnitude is so uncommon that little information is available.

In most cases, increase in the *temperature of the bath* reduces the rate of cooling and may reduce the hardness of the quenched steel. Houghton states that in water and brine the change in cooling rate is small for temperature variations below 38 deg C (100 deg F). Near the boiling point the cooling rate is low, probably due to the formation of low-conductivity vapor in contact with the quenched steel. Increase in the temperature of oil may either increase or decrease the rate of cooling, depending upon the

composition and fluidity of the oil. Figure 100 * shows the center and surface cooling rates of 0.96 carbon steel cylinders $\frac{1}{2}$ in diameter $\times$ 2 in long in water and in No. 2 oil at different bath temperatures.

Understanding of the effect of bath temperature is particularly important where quench tanks are small or where proper circulation is not provided to maintain the bath at constant temperature. Hot water is not ordinarily

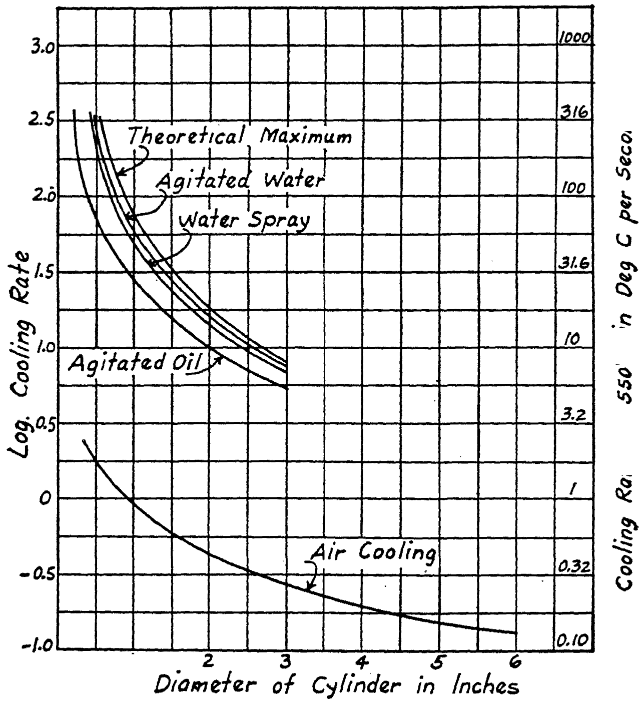



Figure 99. Relationships between size and shape, including calculated maximum theoretical rate of center cooling and comparative center cooling rates of different diameter rounds cooled in several media. (Scott)

considered to be a good quenching medium because of the rapid formation of steam, and for rates between cold water and oil, hot brine or hot sodium hydroxide solutions are frequently used.

The effect of increase in the *temperature of the steel* when quenched is to increase the rate of cooling in the quenching medium. The increase is most pronounced for temperature increases from 700 to 800 deg C (1292 to 1472 deg F), less pronounced between 800 and 900 deg C (1472 and 1652 deg F), and slight above 900 deg C (1652 deg F).

The effect of *diffusivity* of the steel has already been discussed at some length. In general, an increase in the diffusivity of the metal increases

* *ASST Transactions,* **16,** 711 (1929).

the rate of cooling at the center of the piece and decreases the cooling rate at the surface.

The effect of the *surface of the steel* is pronounced in some cases, particularly in the extremes represented by ground and knurled finishes. The smooth surfaces cool faster, probably because gas bubbles do not stick to the smooth surface to the same extent as they do to a rough finish. The

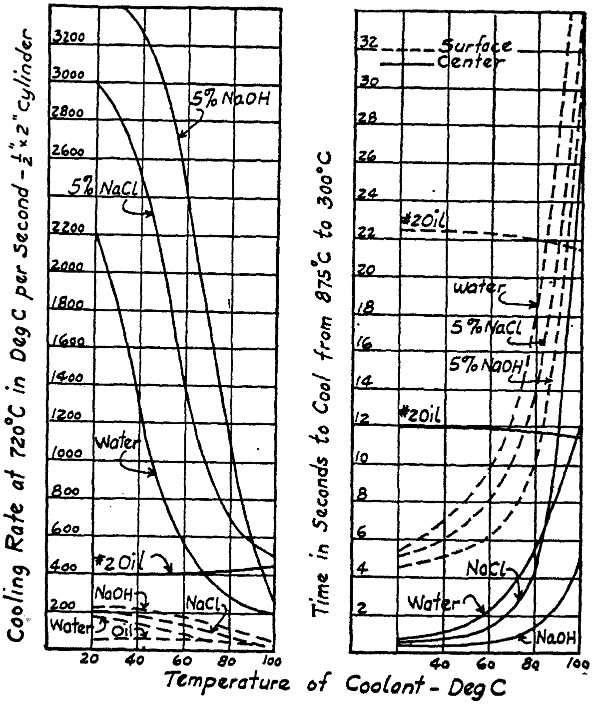



Figure 100. Center cooling rate and surface cooling rate of 0.96° C steel cylinders, ½″ × 2″ in water and oil at different bath temperatures. (*ASST Transactions*, Vol. **16**, 1929)

effect of oxide or scale on the steel is to retard the quenching rate considerably if the scale remains tight during the quenching. Most scale is removed by the action of the bath on immersion and does not affect the quenching rate.

The effect of *gases* formed in the quenching medium is to retard the rate of cooling and to produce soft spots and unevenness in the hardness of the quenched steel.

The *introduction* of the piece into the bath has a considerable effect on quenching results, and the effect varies with the quenching method. These methods vary from dump quenching, in which many pieces are dumped at one time into the tank, to the careful introduction and automatic agita-

tion of the individual pieces. Where many pieces are introduced at one time there is a considerable variation in the quenching effect on individual pieces because of interference with each other. Even the individual quenching methods must be arranged with care for best results. For example, the handling of small bars on prongs which are wet from previous trips into the bath will cause variations in the hardness of the bars. Plunging of pieces into the bath by hand at usual speeds of about 6 feet per second will cause some variation from differences in the personal element involved.

A valuable experimental method used by metallurgists in determining the harden ability of steels in different sizes and under different conditions is the Jominy end-quench test. A standard test bar of annealed steel 1 inch in diameter and about $3\frac{7}{8}$ in long is heated to proper hardening temperature and suspended over a water opening about $\frac{1}{2}$ inch in diameter, with a distance of about $\frac{1}{2}$ inch between the water opening and the end of the test bar. Opening of a quick-acting valve applies water at 60 to 80 deg F temperature squarely against the end of the bar at a rate of about one gallon of water per minute.

After cooling, longitudinal flats are ground on the bar and Rockwell hardness readings are taken at intervals from the end; these are plotted against the distance from the quenched end. The diminishing hardness values from agitated water cooling at the extreme end to no additional hardness will represent the effect of all possible cooling rates in any ordinary quenching medium or in any portion of any size or shape made from the same steel as the test bar.

By extensive experimental work, the relation between resulting hardness on this standard test bar and the hardness at the center of bars of all diameters has been determined for various quenching media. For example, the hardness at $\frac{3}{8}$, $\frac{3}{4}$, $1\frac{1}{16}$, and $1\frac{1}{2}$ in from the quenched end of the test bar is equivalent to that obtained at the center of 1-, 2-, 3-, and 4-in diameter rounds when quenched in still oil.

By casting end-test bars when a heat of steel is made and by reference to the charts, the hardenability of that steel can be predicted for any type of quenching in any finished bar size. The method is also used in selecting substitute steels, and was of great value in the rapid development of the National Emergency (NE) steels for the present war.

## Quenching Media

Methods for the quenching of steel include:

(1) Hand quenching, in which the piece is plunged into the bath by hand.
(2) Gravity quenching, in which the piece falls freely through the bath.
(3) Mechanical quenching, with controlled movement of the piece in the bath.

(4) Fixture quenching, in which the piece is held to shape while being quenched.
(5) Spray quenching, where the piece is flooded with air or liquid from nozzles at high velocity.

Selection of the proper quenching medium depends upon the method of quenching, the nature of the steel to be quenched, the physical properties desired, and the characteristics of the various coolants. As has been previously mentioned, the use of alloy in steel lowers the critical rate of cooling. This permits the use of less drastic quenching media, and reduces the danger of distortion and cracking. For hardening the surface only, an active coolant is desirable.

For most quenching requirements a desirable coolant is one which affords a high initial cooling rate above 500 deg C (932 deg F) to accomplish complete hardening, with a low cooling rate below 400 deg C (752 deg F) to reduce the amount of residual stress, which causes distortion and quenching cracks.

The first stage in quenching action is the formation of vapors; this is objectionable and is controlled by agitation of the bath, low coolant temperatures, selection of good quenching oils, or addition of salts to water quench solutions. The second stage is the rapid cooling stage, where water is more active than any oil. The third stage is the slow cooling stage, where oils are particularly valuable because of the rapid change in rate with temperature. The best quenching oils retain constant quenching properties because they do not change in composition with use, as the result of either oxidation, decomposition, or distillation. The usual quenching oil has a specific gravity of about 0.88 (water is 1.00), a flash point of from 200 to 300 deg C, a boiling point between 375 and 400 deg C, a specific heat of about 0.49, and weighs about 7.38 lbs per US gallon.

The comparative cooling speeds of several common liquid coolants is given in the following tabulation by French, where 0.96 carbon steel cylinders $\frac{1}{2}$ in diameter $\times$ 2 in long were quenched in liquid having a circulation of 3 ft per second in every case:

| Liquid and temperature | Cooling time (sec from 875 deg C to 200 deg C [1607 to 392 deg F]) | |
|---|---|---|
| | Surface | Center |
| 5% NaOH at 20 deg C (68 deg F) | 0.31 | 7.8 |
| 5% NaCl at 20 deg C | 0.48 | 7.4 |
| Water at 20 deg C | 1.2 | 8.6 |
| 5% NaOH at 60 deg C (140 deg F) | 1.0 | 8.8 |
| 5% NaCl at 60 deg C | 1.8 | 11.8 |
| Water at 60 deg C | 3.2 | 13.4 |
| 5% NaOH at 80 deg C (176 deg F) | 3.1 | 14.2 |
| No. 1 Oil at 20 deg C | 14.7 | 28.8 |
| No. 2 Oil at 20 deg C | 19.3 | 29.7 |

### Quantity of Coolant Required

Where oil is used as the quenching medium the usual rule for quench tank capacity is one gallon of oil for each pound of steel quenched per hour. This tank capacity can be somewhat smaller where separate oil coolers and circulating pumps are used, but the use of this figure will avoid any difficulties with the control of oil temperature and will allow for intermittent quenching of steel, which increases the cooling requirements for short periods well above the average requirements. Where this intermittency is pronounced, as in the case of large charges from a batch type furnace to be quenched at considerable intervals, a better rule is to provide one gallon of quenching oil for each pound in the largest mass to be quenched at any one time. In such cases it will be found that physical space requirements frequently take care of this provision automatically. Because water quenching temperatures should usually be lower than are satisfactory for oil, it is a good plan to follow the same rule for determining the size of water tanks, in spite of the higher specific heat of water as compared with oils.

### Circulation and Cooling of the Coolant

The two methods for proper control of oil temperatures in quenching are the use of an external cooler with circulating pump, and cooling pipes in the tank with proper circulation.

In the first arrangement the oil is drawn from the top of the tank by the pump and moved to the cooler. From the cooler the oil passes to a storage tank or directly to the bottom of the quench tank. Recommended circulation is between 3 and 4 gallons of oil per hour for each pound of steel quenched per hour, and a water circulation through the cooler of about the same amount. Types of oil coolers are illustrated below.

Figure 101. Small portable cooler with self-contained pump and cooling coils for circulating and cooling oils.

In the second arrangement, water pipes are arranged along the sides of the tank for cooling the oil. Sheet steel baffles are provided on all four sides to provide a channel between them and the sides of the tank, with the

cooling pipes located in this channel. The oil flows over these baffles down past the cooling pipes and to a propeller at the bottom, which drives the cooled oil directly at the steel as it arrives on the conveyor in the tank. This propeller is driven through a packing gland by a motor outside the tank. The amount of water cooling pipe per pound of steel quenched in any hour is about 0.14 ft of 3-in wrought-iron pipe, 0.21 ft of 2-in pipe, or 0.38 ft of 1-in pipe. The water circulation through these pipes is about 1.5 gallons of water for each pound of steel quenched per hour.

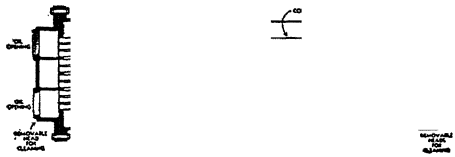


Figure 102. Cross-section of typical oil cooler.

## Equipment for Circulating and Cooling Oil

In some cases quenching oil is pumped to tanks on the roof and is allowed to flow down long metal chutes covered with wire mesh to produce increased agitation and greater cooling. In other cases small portable coolers with self-contained pump and cooling coils as shown in Figure 101 are used, but the most up-to-date installations of any size employ either oil coolers or special tanks as have been described.

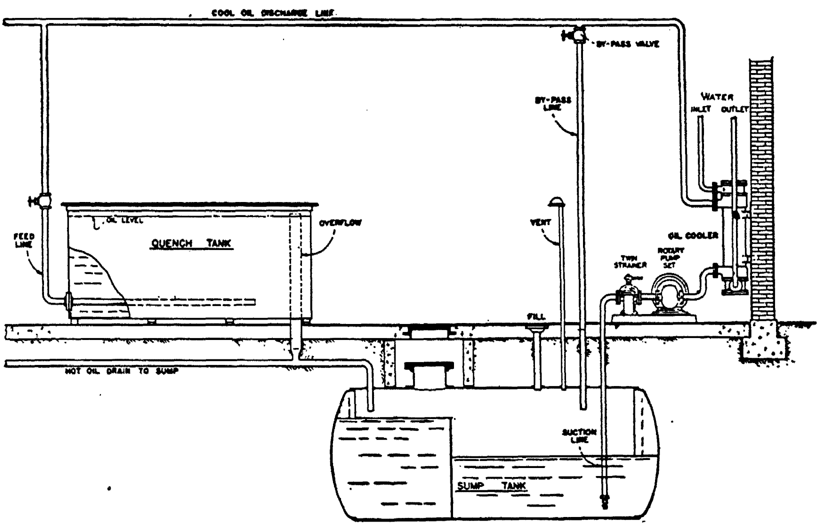



Figure 103. Diagrammatic representation of arrangement for externally cooling oil.

Figure 102 shows a cross-section of a typical cooler with water-cooled oil tubes. Figure 103 is a diagram of the arrangement for externally

cooling oil. Figure 104 shows the type of quench tank with propeller and internal water-cooling pipes. The propeller motor is shown clearly in the photograph, and an interesting feature of the installation is the discharge

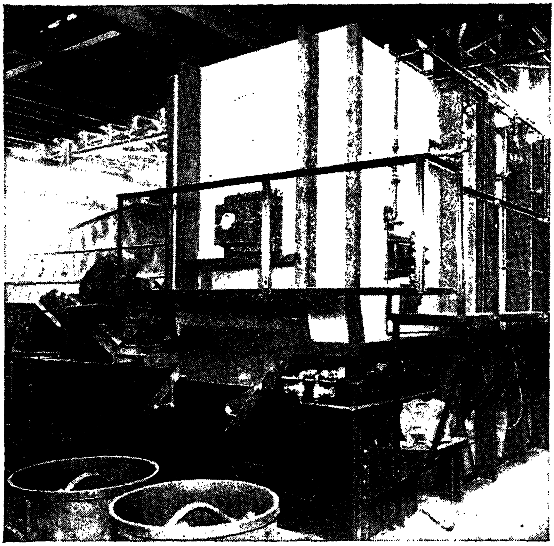


Figure 104. Quench tank with propeller and internal water-cooled pipes. Discharge chute is of the double-pass type, permitting by-passing material into either quench tank or tote boxes.

chute of double-pass type, permitting the discharged material from the furnace to pass either into the quench tank or directly to tote boxes when the furnace is used for tempering.

## Types of Quenching Equipment

**Batch-type Quenching.** The simplest type of hand-quenching involves a batch-type furnace in conjunction with a quenching tank containing a basket for holding the quenched pieces; this method is common in job shops for intermittent work. The pieces are usually removed individually from the furnace with tongs, plunged into the quench, circulated in the coolant for several seconds, and finally allowed to fall into the basket in the bottom of the tank. The basket is removed at intervals from the tank by means of a crane or individual hoist. In some cases, the pieces are placed in racks in the tank for selective quenching of a part of the piece.

Wire baskets are shown in Figure 105, and Figure 106 illustrates a basket of perforated alloy sheet with detachable handle for cyanide hardening, where the basket is heated in a salt bath and its load of steel parts is dumped into the quenching bath.

A variation in the usual basket arrangement is the elevator design of Figure 107, in which the movement of the basket is controlled by a double-acting air cylinder. The necessity for overhead lifting equipment is eliminated, and the basket may be readily agitated in the bath by operation of the air valve if desired. Provision is also made for draining this tank,

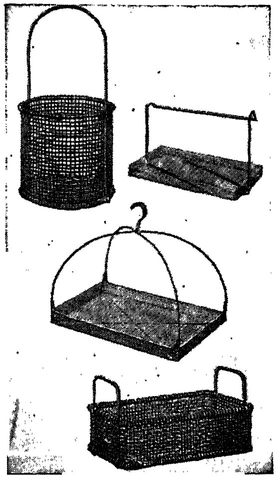


Figure 105. For batch hardening, dipping baskets of woven wire similar to that shown may be used.

and a bottom screen is provided for readily removing all scale and lost pieces. Figure 108 illustrates another special elevator quench tank. In this case, sheet-metal aircraft parts are heated in the furnace shown and are run out on the elevator, which quickly lowers the pieces into the tank. The very light section of the sheets in this case requires quenching within five seconds after removal from the furnace.

Another interesting variation in elevator quenching is shown in Figure 109. This installation is for the heat-treating of aluminum connecting rods for

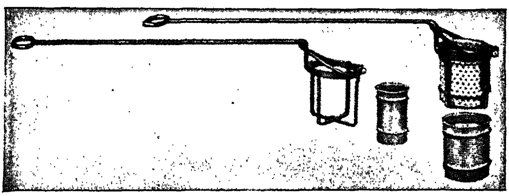


Figure 106. Dipping basket of perforated alloy, with detachable handle, for cyanide hardening.

aircraft motors, and the furnace is an overhead chain conveyor type from which the rods are suspended in groups. The conveyor is operated intermittently to discharge one group of rods at a time. When this group of rods arrives over the quench tank, as shown in the illustration, the entire quench tank is elevated to submerge the rods. After the proper interval of time the tank is lowered and the chain conveyor advances again.

Another batch-quenching problem is involved in the quenching of long rods or other articles in a vertical position, such as guns and aircraft fuselages after assembly. Pieces up to 80 feet in length and weighing up

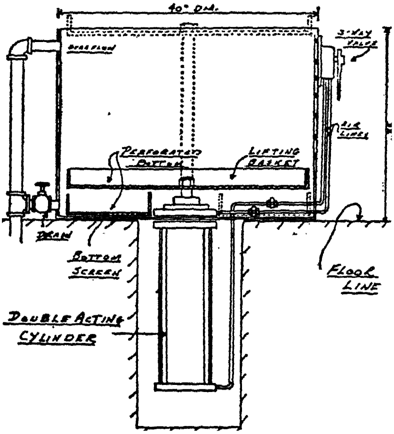



Figure 107. Variation in the usual dipping basket arrangement provided by the use of a double-acting hydraulic cylinder to manipulate the basket.

to 75 tons are hung in a vertical furnace for heating and are then transferred by a crane from the top or side of the furnace and immersed vertically into the top of a quenching tank. It is interesting to note that forgings weighing 40,000 pounds can be quenched in about 18,000 gallons of water,

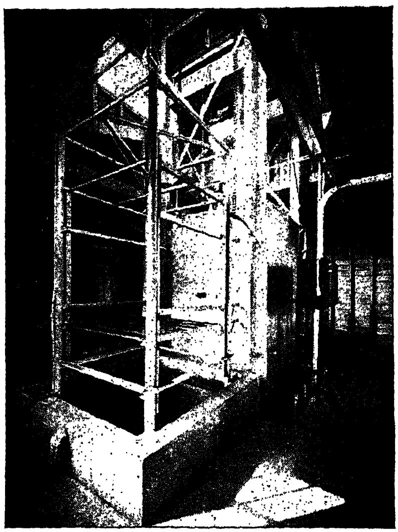


Figure 108. Specially designed elevator quench tank used in the heat treatment of sheet-metal aircraft parts.

which is considerably less water than is recommended for continuous quenching of smaller pieces. Under these conditions there is a large initial water loss from the top of the tank when the piece is immersed and a large

amount of steam is formed, which apparently does not adversely affect the metallurgical results in the case of such a large mass. Fabricated structures, such as those made from tubing of light section, must be quenched quickly from the heating furnace; one method is to arrange the quench tank directly below the furnace so that the piece may be quickly lowered through the bottom of the furnace into the tank.

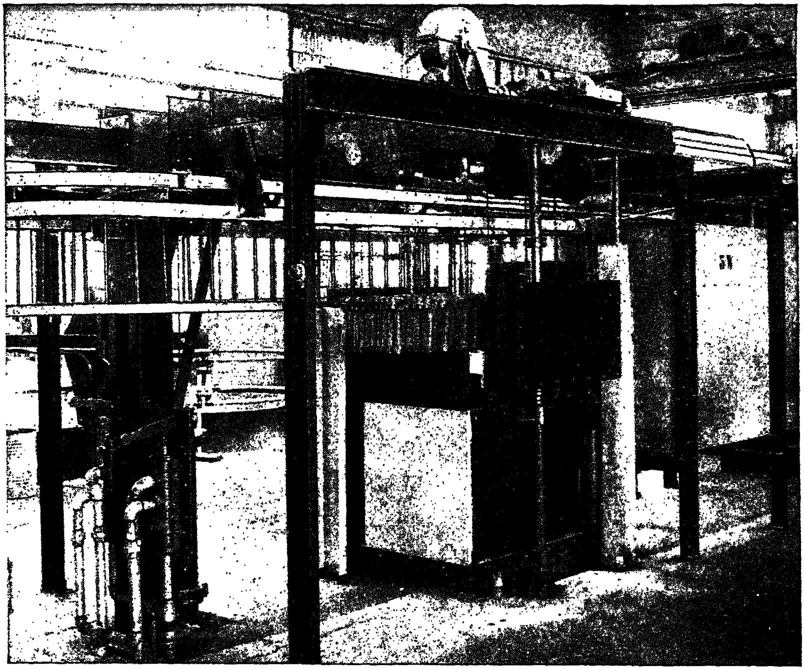


Figure 109. Elevator quenching installation in conjunction with overhead chain conveyor type furnace for heat treatment of aluminum connecting rods for motors.

A batch arrangement for bars comprises a roller hearth furnace for heating, a roller run-out table, special handling crane, and tank. In operation the heated bars in single layer are run out on the motor-driven table. The bars actuate a limit switch at the end of the table, which causes the crane to lift about 6 in to clear the rolls, the bars being carried on the fingers of the crane which are between the rolls in the lowered position. The crane then passes automatically over the tank and submerges the load of bars. In some cases the crane fingers do not stop in the tank, but raise and lower slowly from the top to the bottom of the bath, in order to wash all bar surfaces and prevent temperature rise of the coolant in contact with the bars.

An automatic timer causes the crane to lift the load out of the tank for a sufficient draining period. Automatic timing permits accurate duplication of quenching cycles, and insures that the steel is withdrawn from the tank

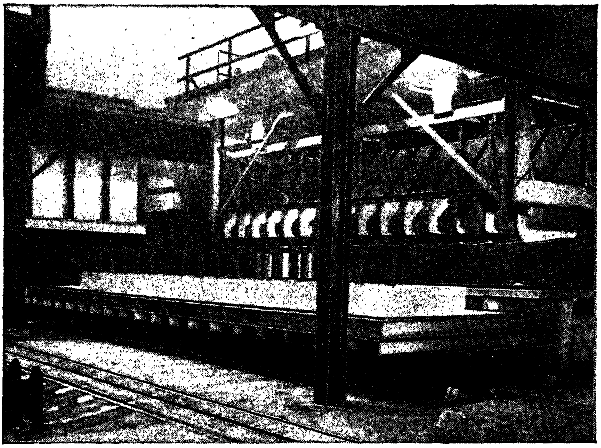


Figure 110. Quenching arrangement for bars for use in conjunction with car-type bell furnace.

at exactly the right time. This is important with some alloy and carbon steel grades, which crack, check, or split if cooled to too low a temperature in the coolant.

A similar quenching arrangement is used in conjunction with a car-type bell furnace, as illustrated in Figure 110. In this case the bars are supported on bucks on the car, from which they are lifted by crane fingers and trans-

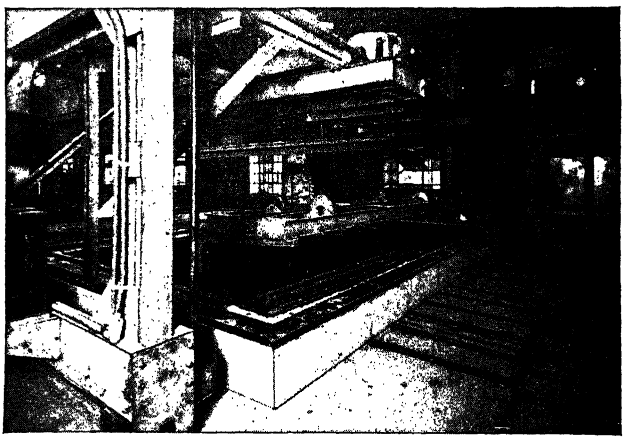
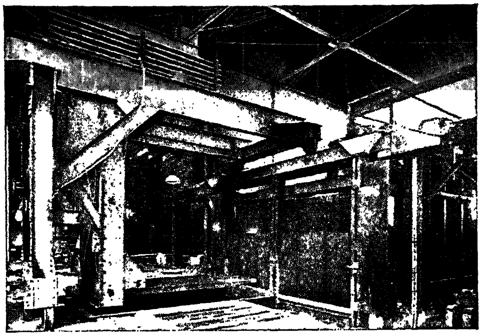


Figure 111. Quenching arrangement for bars employed in conjunction with ordinary car-type furnaces. A gantry crane handles the bars.

ferred to the quench tank with all of the automatic features already described. In one such installation, 10,000 pounds of steel are quenched at intervals of about one hour in a quench tank containing 10,000 gallons of oil. A similar arrangement with gantry crane and ordinary car-type furnace for bars is shown in Figure 111. In another piece of equipment for quenching truck frames the crane is a simple cable suspension from a floor-operated trolley.

In all the foregoing quenching arrangements employing a crane, the material has been moved out of the furnace and then picked up by the crane fingers. A variation of this is the arrangement of Figure 112, where a gantry crane of special design is provided with prongs which enter between longitudinal piers in the furnace. These prongs lift the material out of the

Figure 112. In this installation, gantry crane of special design is provided with prongs which enter the furnace between longitudinal piers and lift the material quickly from the furnace and into the quench tank in the foreground.



furnace and deposit it quickly into the quench tank located in front of the furnace. This arrangement is particularly adaptable for heat treating castings and other chunky pieces, and can be applied to a maximum furnace depth of about 10 feet. The furnace doors are electrically operated, with controls in the operating cab at the rear of the crane. In this particular installation, two oil-fired furnaces are built in a common setting to make a very compact heat-treating unit where, after heating and quenching, the material is returned to the second chamber for tempering.

**Continuous Quenching.** By continuous quenching is meant the continuous movement of individual pieces through the furnace and into the quenching bath. In many cases the pieces pass from the quenching tank continuously into a second furnace for drawing or tempering treatment. The principal requirement in this process is a reliable and fool-proof handling method, and many interesting devices have been employed.

A simple and satisfactory quenching machine for small parts is the spiral rotating quench tank of Figure 113, which consists of a perforated cylinder inclined in a rectangular tank. Inside the cylinder is a spiral screw, and the cylinder is rotated by motor drive. The rotation of the spiral moves the pieces continuously and prevents any piling or objectionable contact

while quenching, so that a high degree of uniformity of hardness is obtained. The machine shown in the illustration will handle pieces under 10 in long, and will quench up to 5000 lbs of steel per hour.

Two of these quenching machines are sometimes used in conjunction with a furnace. One tank contains oil and the other tank is for quenching

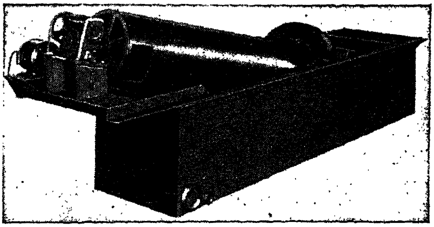


Figure 113. A perforated cylinder inclined in a rectangular tank. Inside cylinder is a spiral screw, and the cylinder is rotated by motor drive.

in water, and the chutes are arranged for discharging to either tank as desired.

Figure 114 shows a chain-belt furnace fired by radiant tubes to avoid any contact of combustion gases with the heating material, and filled with protective gas atmosphere. The pieces are discharged from the belt to a chain conveyor in the quench tank, which is provided with a propeller for circulating the water but does not have cooling means within the tank. Provision is made for disconnecting the sealed chute when it is desired to move the tank away from the furnace. Wheels are mounted on the tank, and a cylinder is provided for moving the tank.

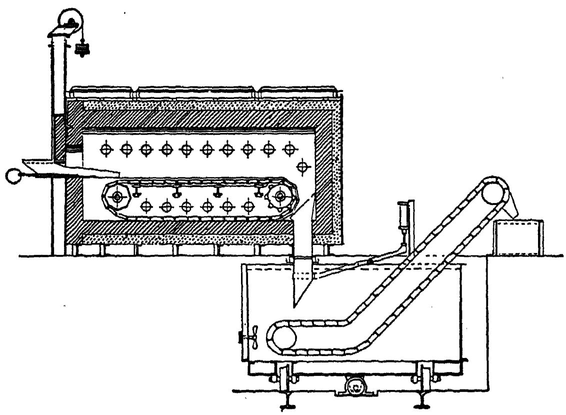


Figure 114. Chain-belt furnace fired by radiant tubes to avoid any contact of combustion gases with the heating material, and filled with protective gas atmosphere.

Conveyor-type quench tanks are commonly used for a variety of pieces and with many kinds of continuous furnace. Figure 115 includes a quench tank with conveyor made of woven wire mounted on chains at both sides, which will handle pieces up to about 10 lbs in weight. This tank also has an agitating propeller driven from the outside, but does not have internal

cooling coils. Conveyors in quench tanks are always driven at the head shaft at the discharge end, to place the working portion of the conveyor in tension and because this end is above the level of the coolant. Variable-

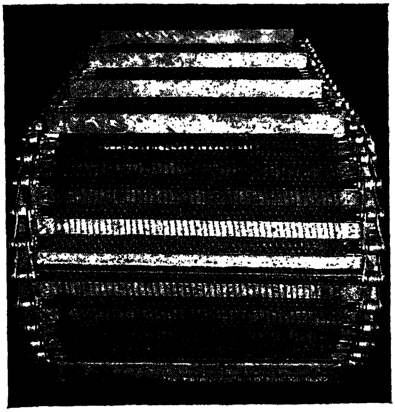


Figure 115. Quench tank with conveyor made of woven wire mounted on chains at both sides, which will handle pieces up to about 10 lbs in weight.

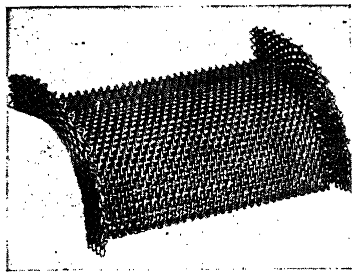


Figure 116. Woven wire conveyor with turned-up selvage edges, which can be used for small pieces.

speed drive is provided to permit adjustment of the quenching time and to synchronize the quench-tank speed with that of the continuous furnace. Figure 116 shows a woven wire conveyor with turned-up selvage edges, which can be used for small pieces.

Figure 117. Heavier type of quench conveyor in which the flights are constructed of heavy perforated plate arranged in steps, to hold the pieces on the inclined portion of the conveyor.

Figure 117 illustrates a heavier type of quench conveyor in which the flights are constructed of heavy perforated plate arranged in steps, to hold the pieces on the inclined portion of the conveyor. In this case the conveyor of the quench tank discharges into a washing machine, to remove quenching

oil before the pieces enter the drawing furnace at the rear of the illustration. The mechanism shown in the foreground drives both the tank conveyor and the furnace belt. Figure 118 is another flight-conveyor quench tank for heavy pieces, used in conjunction with a chain-conveyor furnace. This tank is of the propeller type with internal water coils located in channels shown at the sides of the tank, as has been previously described. The conveyor discharges into a tote box as shown. Also shown in the illustration

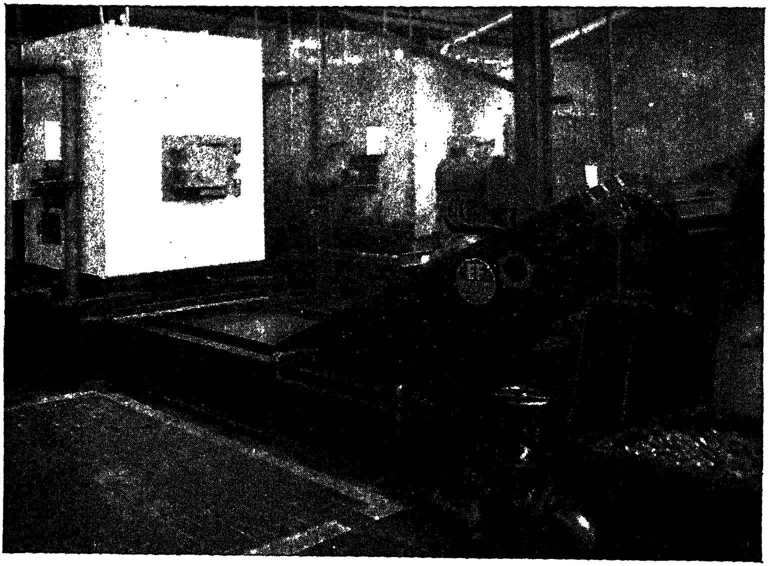


Figure 118. Flight-conveyor quench tank for heavy pieces, used in conjunction with a chain-conveyor furnace. This tank is of the propeller type with internal water coils located in channels shown at the side of the tank. The conveyor discharges into a tote box as shown. Note protective gas generator for supplying protective gas to the furnace for clean or bright heating.

is a protective gas generator for supplying protective gas to the furnace for clean or bright heating.

A conveyor quench tank in conjunction with a chain-belt hardening furnace and a chain-type drawing furnace is shown in Figure 119. Tractor parts are heat-treated in this equipment and are handled automatically from the charging end of the hardening furnace to the tote boxes at the discharge end of the drawing furnace. A considerable extension of the conveyor in the quench tank is made to gain sufficient elevation for sliding onto the drawing furnace conveyor; this distance provides time for the pieces to drain, with excess oil running back into the tank.

Figure 120 shows two flight-conveyor quench tanks with two chain-belt furnaces for heat-treating can openers and other small parts. A feature

of this installation is the roller tables in the floor for ease in moving the tote boxes at the discharge end of the quench conveyors.

A heavy flight-conveyor quench tank is shown in Figure 121 with a pusher-type furnace for heat-treating large tractor parts. A feature of

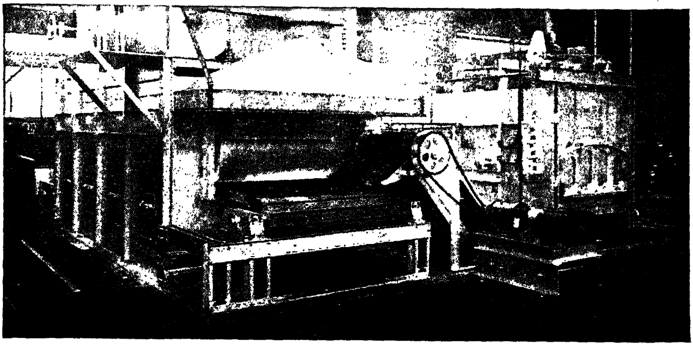


Figure 119. Conveyor quench tank used with chain-belt hardening furnace (right background) and chain-type draw furnace (foreground), for heat-treating tractor parts.

this tank is the ratchet drive, and the ratchet wheel is shown at the far side of the head shaft. This wheel is driven by a reciprocating pawl driven by motor and gear reduction units. Circulation in this tank is obtained by nozzles shown at the side.

A double quench tank for oil or water appears in Figure 122 for quenching pieces heated in a continuous rotating-hearth furnace. The pieces may be

Figure 120. Two flight-conveyor quenching tanks with two chain-belt furnaces, for heat-treating can openers and other small parts.

deflected to either tank in the divided chute from the furnace. The circulation in this case is by propeller at the bottom of the oil tank, and cooling is accomplished by internal water pipes in the channels clearly shown at the sides of the oil-quenching tank. A flight conveyor delivers the pieces from the tank to the tote baskets. Another arrangement of rotating-hearth

furnace for quenching in either oil or water has two chutes from the furnace at the two adjacent doors, one to each tank. By reversing the rotation of the hearth the pieces may be discharged to either tank, with the other door in either case used for charging.

Figure 123 illustrates a chain conveyor for handling automobile drive shafts from a quench tank to a draw furnace, as part of a completely automatic heat, quench, and draw equipment for these pieces. The electric and oil-hydraulic pulpits and other control equipment appear beyond the

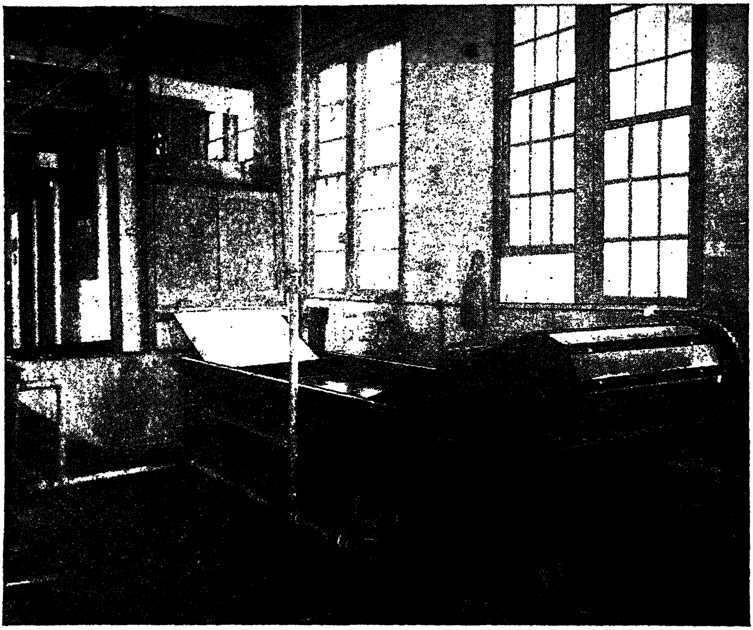


Figure 121. Heavy flight-conveyor quench tank used with pusher-type furnace for heat-treating large tractor parts. Note ratchet drive at far side of head shaft.

tank. Particular attention must be paid to the chute design in this case to insure that the pieces are deposited accurately on the conveyor chain. In this installation an elevator mechanism was used at the discharge end of the hardening furnace to eliminate the difficulties with gravity discharge of such pieces, which are of larger diameter on one end than on the other.

A similar but unique installation is shown in Figure 124 where drive shafts are again the heated material. Here, the shafts are gravity-discharged from the hardening furnace to the quench tank, with an escape mechanism provided for registering the shafts on the chain. Lugs on the conveyor chain in the tank move the shafts forward at desired speed while a second chain in the tank causes the shafts to spin at a speed of 150 rpm

while quenching. Oil circulation is obtained by jets and the uniformly quenched shafts are automatically charged on the conveyor of the draw furnace at the rear of the illustration.

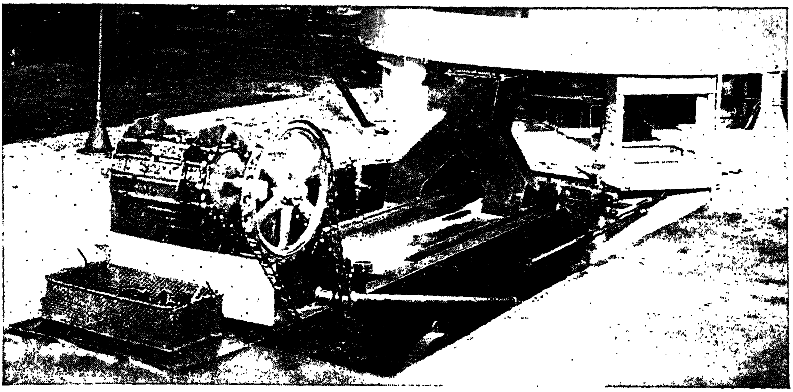


Figure 122. Double quench tank for either oil or water-quenching of pieces heated in a continuous rotating-hearth furnace. Note Y-shaped chute for deflecting pieces to desired bath.

An installation for individually quenching bars appears in Figure 125, where the bars drop one at a time on to a counterweighted cradle, such that the weight of one bar is sufficient to sink the cradle and bar into the circulating oil in the tank. Further agitation of the bar in the oil can be manually obtained by means of the handle at the center. The bars are removed in

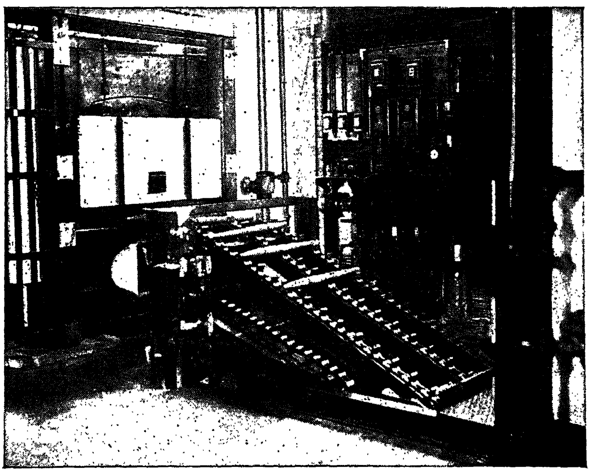


Figure 123. Chain conveyor for handling automobile drive shafts from a quench tank to a draw furnace.

batches from the tank by means of a permanent cradle in the tank, which can be lifted by the crane.

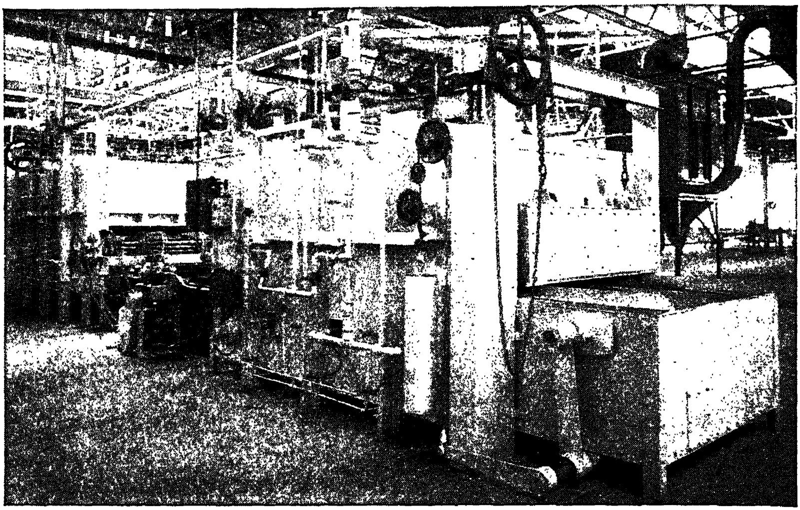


Figure 124. Furnace installation for heat treatment of automobile drive shafts. Lugs on chains in quenching tank move shafts forward at the desired speed while second chain rotates them at 150 rpm while quenching.

A diagrammatic view of a continuous carburizing equipment without muffles is given in Figure 126; this equipment includes an interesting

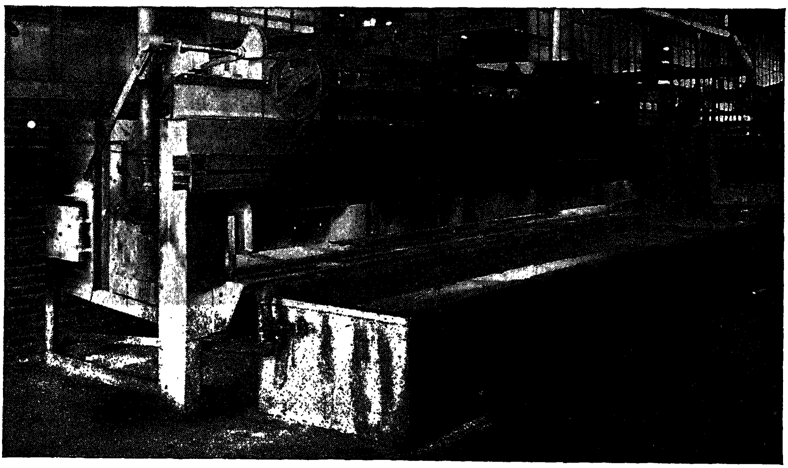


Figure 125. Side-discharge furnace and quenching equipment installation for individually quenching bars, where bars drop one at a time on to a counterweighted cradle, such that the weight of the bar sinks it and cradle into bath.

quench. The entire unit is arranged with protective gas to exclude all air, and the carburizing and reheating furnaces are radiant-tube fired and provided with gas-filled vestibules. All operations are by pusher, and the container with carburized parts is pushed into the gas-filled oil-quenching chamber from the reheating furnace. An elevator in the quenching chamber lowers the container quickly into the oil and holds for an automatically

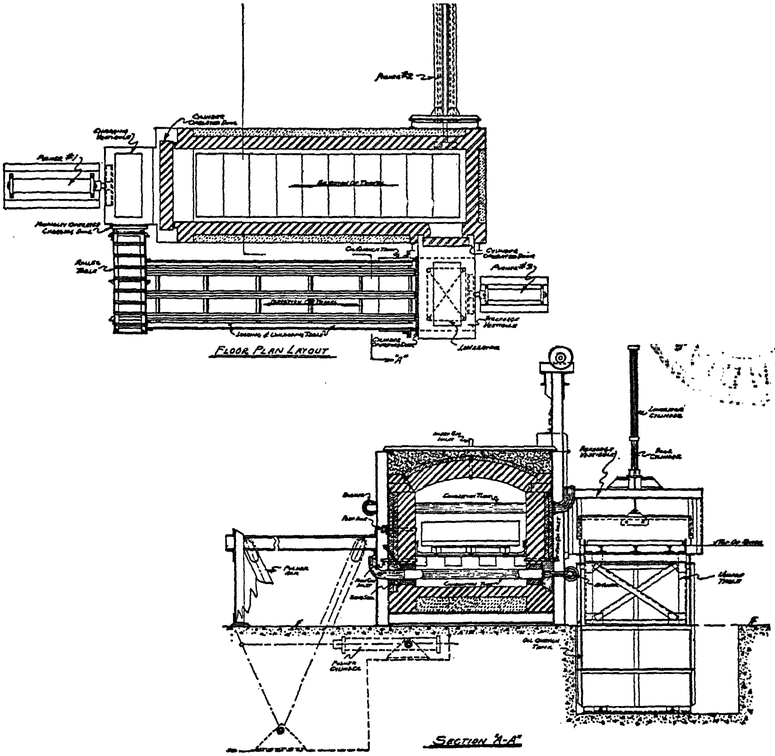



Figure 126. Muffleless continuous carburizing equipment with controlled atmosphere, provided with elevator for lowering containers into oil bath and holding for a predetermined time, followed by a holding period for drainage.

controlled time interval. The elevator again rises and holds for a predetermined time for drainage, when the container is pushed into chambers for washing and rinsing, and then into the final draw furnace.

As a final illustration of continuous quenching, the automatic equipment of Figure 127 is given. This device is for continuous heating, quenching, and washing of small pieces. The container is first preheated by waste gases from the salt bath, then moved into the salt pot for heating. It is then moved to the oil-quenching bath and finally to the rinsing bath. The

containers are suspended from small roller carriages operating on a monorail. Movements are made by rotating arms operating in unison, and the carriages are finally placed on a sloping monorail and removed by gravity.

**Fixture Quenching.** Fixture quenching applies to articles which must be heat-treated in straight or cambered form without being warped or distorted by the treatment. Since most of the warping occurs in the quenching tank, provisions are made for mechanically holding the piece while quenching. Examples of this type of quenching are ring gears, rods, and threaded couplings for pipes.

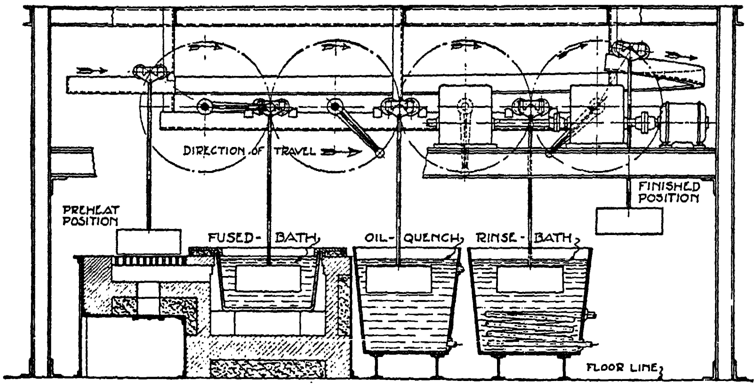



Figure 127. Arrangement for continuously heating, quenching, and washing of small pieces. Preheating is accomplished by waste gases, as shown. Fused salt bath is used for heating.

Figure 128 illustrates an automatic quenching press for quenching ring gears without distortion. The gears are held both round and flat by control of the oil circulation and by light pressure at the proper points while cooling, and no strains are set up during the operation. The gear is placed on the lower die and the upper die descends to clamp the gear while hot and plastic. The assembly is then submerged in the oil, fresh oil being forced through the teeth of the gear at a rapid rate. At the expiration of a predetermined time interval the assembly rises and opens, and the gear may be removed. Special oil circulation is designed into the dies. The press is built to handle up to 25-in diameter gears and will quench from 10 to 50 gears per hour, depending upon the metal section. From 10 to 30 gallons of oil per minute must be circulated, depending upon temperature of the oil entering the press and assuming an outlet oil temperature of 115 deg F. The oil is supplied to the presses from an outside reservoir or cooling system.

Another device is a centrifugal-fixture quenching machine for circular parts, including gears, sprockets, discs, flat cams, rings, and bearing races. In this machine the piece is placed in a bottom fixture, and the holding

fixture is automatically operated. The fixtures are surrounded by a circular quenching chamber in two parts, which open with the fixture. After closing, the entire assembly is rotated by motor drive and the quenching fluid is introduced in controlled quantity and at controlled temperature into the chamber. The advantages of the machine include accurate control of alignment, time, volume of quenching medium, and temperature of

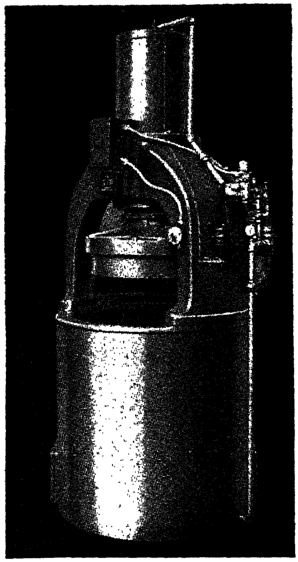


Figure 128. Automatic quenching press for quenching ring gears without distortion.

the medium. The speed of operation is high, requiring only 40 to 60 seconds for a complete cycle of operation for an average gear or sprocket.

Figure 129 shows a quenching machine for automobile stabilizer shafts, which are complicated in design and costly to straighten after quenching. In this machine a hot straight bar is taken from a furnace at quenching temperature and placed in the machine, which bends it to proper position and holds it while it is quenched.

In a similar machine, steering arms are formed and quenched while held in position, which eliminates the necessity for cold straightening. With this method it is claimed that the maximum physical properties of the steel are obtained, the hardness is uniform, and the piece will retain its shape when subjected to road shocks, because no hardening stresses have been set up.

A machine for straightening and quenching front axles is shown in Figure 130. These axles are forged one at a time, which makes it impossible to hold an accurate length, and usually requires a heating and stretching operation. With this machine, the axle is taken from the hardening furnace and stretched. The machine then quenches the axle while holding it in

position. A variation of this machine rotates the axles rapidly while quenching to insure straightness. A jig with rotating rollers to turn the axle is immersed in the quench tank.

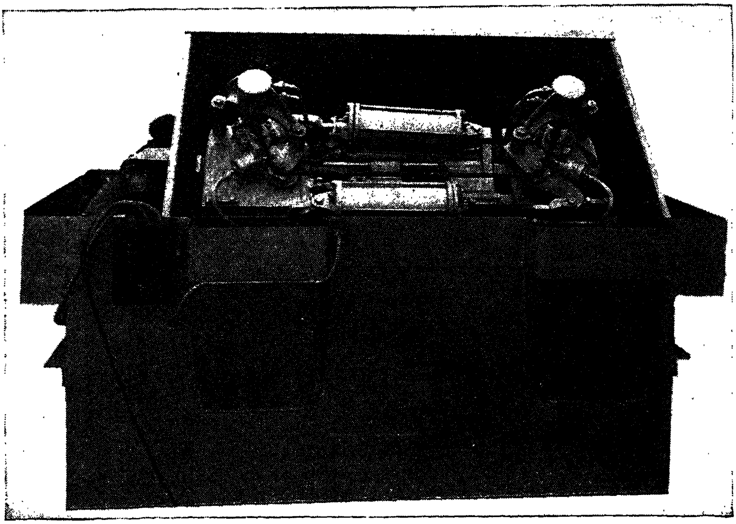


Figure 129. Quenching machine for automobile stabilizer shafts, designed to minimize distortion of the shafts during quenching.

Figure 131 includes an interesting quench tank as a part of an installation for the heating and fixture-quenching of rods up to 30 ft long and

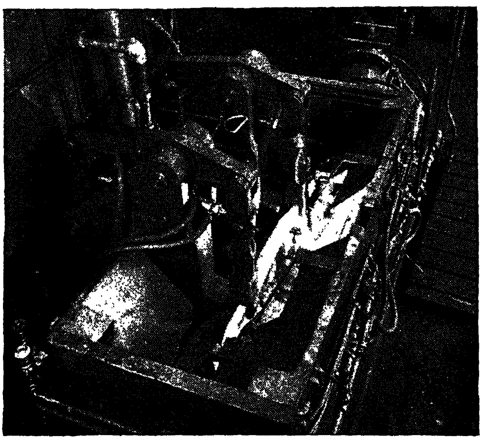


Figure 130. Machine which subjects forged axles to a stretching operation to establish proper length and quenches them in position, to eliminate distortion.

from $\frac{1}{2}$ to 1 in diameter. The device automatically pulls the rod from the heating furnace and deposits it in a jig for holding it straight. The jig submerges in circulating oil and is held for an automatically controlled

time interval. The jig then rises automatically and opens, when the rod is transferred by the mechanism to the receiving cradle.

**High-temperature Quenching.** This group includes all processes where the steel is quenched in hot liquids or molten metal, and outstanding

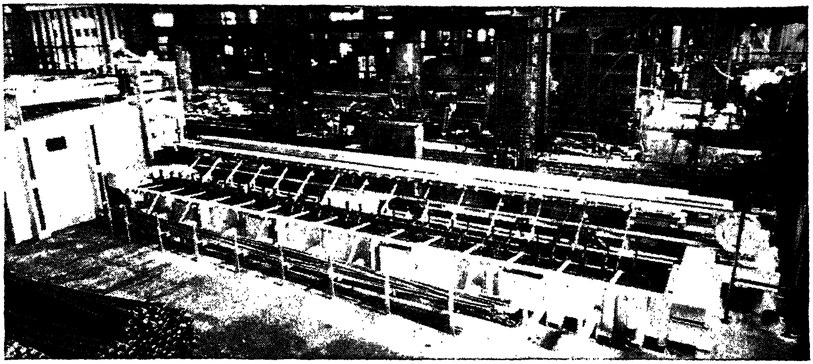


Figure 131. Quench tank for the fixture-quenching of long rods up to 30 ft in length and 1 in in diameter.

examples are Austempering and wire patenting. Austempering is a process of quenching at an elevated temperature in order to obtain ductility as well as hardness without the necessity for further drawing; but the process is applicable only to small sections. Figure 132 shows a salt bath quench used in this process. The salt is heated by means of radiant alloy tubes

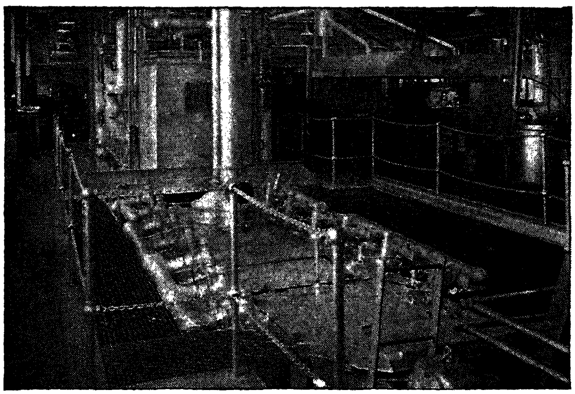


Figure 132. Salt bath quench used in an Austempering operation to obtain desired ductility and hardness of parts without subsequent drawing.

immersed in the salt bath, and gas is burned in the tubes by means of burner mounted at one end of the tubes, as shown in the illustration.

In the patenting of wire or rods, a number of strands are frequently pulled through an open patenting furnace and into a lead pot at the discharge end of the furnace. A typical arrangement involves 24 strands of

0.215 in diameter rod passing through the furnace and lead pot at a speed of 22 ft per minute, which is a production of about 4000 lbs of rod per hour. The rod leaves the furnace at a temperature of 1700 deg F and is quenched in lead at a temperature of 1000 deg F. The furnace is 60 ft long and is operated at a temperature of about 1900 deg F, while the lead tank is 18 ft long × 4 ft wide × 9 in deep. The time in the furnace is about 2.7 minutes and in the lead bath about 49 seconds.

**Flood Quenching.** This interesting variation in quenching is used in special cases for certain types of individually quenched pieces, for non-ferrous quenching in some cases, and where quenching speeds are desired which cannot be obtained in liquid baths.

An automatic selective quenching machine based upon the flood-quenching principle is shown in Figure 133 and is used for the selective quenching

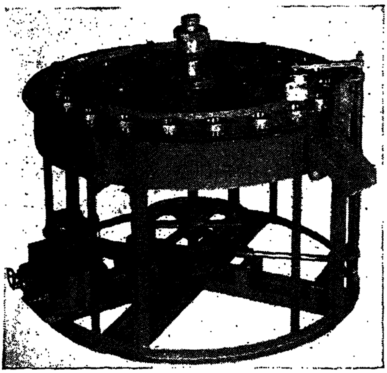


Figure 133. Automatic selective quenching machine based upon the flood-quenching principle. Used for selective quenching of rock bits.

of rock bits. In this case it is desired to obtain a very high degree of hardness on the cutting edges while retaining toughness in the body of the tool, to withstand the repeated shocks involved in rock drilling by compressed air. The bits from the furnace are placed in the flood-quenching heads which rotate in the continuous operation of the machine. After flooding a portion of the tool for a predetermined time, the partially cooled piece is removed automatically by the solenoid mechanism and dropped on the chute which leads to the secondary quench tank for properly cooling the body of the piece from the residual temperature remaining after the flooding of the cutting surfaces.

Machines similar to that of Figure 133 are also made to quench pieces rapidly by means of compressed air. In one such machine, 100 pieces weighing 1.5 lbs each are quenched per hour from 2000 deg F to 1300 deg F in 30 seconds under very accurately controlled conditions, with a consumption of 500 cu ft of air per minute at a pressure of 80 lbs per sq in. The time to cool the same piece to the same extent in still air is 3.5 minutes,

and in air at a velocity of 200 ft per second (air at about 8 oz pressure) the time required is 65 seconds.

In the partial quenching of steel pieces from one temperature to another temperature above that of usual liquids, air is frequently employed, and an understanding of the effect of velocity on cooling is important. This relation may be expressed by the formula:

$$C = 1.0 + 2.7\,DV$$

where $C$ = Coefficient of heat transfer between the air or other coolant gas and the steel surface, in Btu per square foot of steel surface per hour per deg F temperature difference between the gas and steel surface
$D$ = Density of the coolant gas in pounds per cubic foot
$V$ = Velocity of the coolant gas in feet per second

The velocity of air from a nozzle for any air pressure below 10 lbs per sq in may be quickly determined from the formula:

$$V = 66.35\,K\sqrt{H}$$

where $V$ = Velocity of air from the nozzle in feet per second
$K$ = Discharge coefficient which is from 0.8 to 0.9 for most cylindrical nozzles
$H$ = Pressure drop through the nozzle in inches of water

Using the above equations, the velocity of air at 8 oz pressure is 210 ft per second, so that the coefficient for cooling air at this pressure is 44 Btu per sq ft per hour per deg F. Similarly, the coefficient of heat transfer for air at 1 lb pressure is 62, and the coefficient for air at 10 lbs pressure is 194.

A flood-quenching chamber in connection with a continuous roller hearth heat-treating unit is shown in Figure 134, where water sprays are used for the quenching. This arrangement is most often used for non-ferrous bars and coils, but is also applicable for certain steel-treating processes.

**Surface Hardening.** Another special quenching operation is surface hardening. This consists in a localized heating of the steel surface, followed

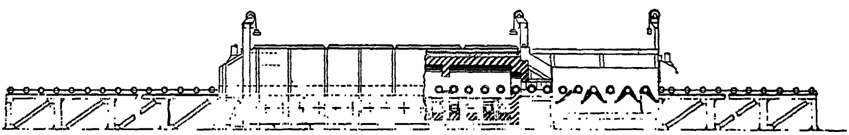


Figure 134. Flood-quenching chamber in connection with a continuous roller hearth heat-treating unit. Water sprays are used for the quenching. This arrangement is most often used for non-ferrous bars and coils, but is also applicable for certain steel-treating processes.

by quenching, and the result is a hardening of the surface of the steel to some desired depth. The hardness beyond this depth tapers off gradually and the stresses produced are very small, so that intricate shapes like gear teeth may be hardened with a minimum of distortion or cracking. Surface

hardening of gear teeth avoids the expensive necessity for machining the teeth from very hard blanks, and is similar in effect to nitriding or case-hardening.

Figure 135 illustrates a method for hardening with oxy-acetylene torches. The complete machine set up for hardening the teeth of a large gear is

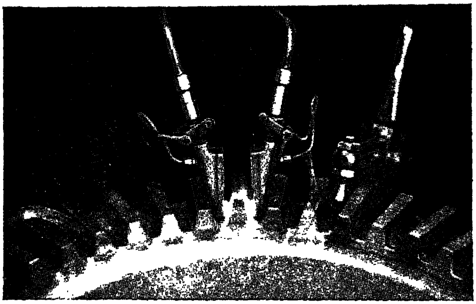


Figure 135. Method for hardening with oxy-acetylene torches.

shown in Figure 136. The speed of the heating burners is automatically adjusted to suit the requirements of the piece, and the quenching is usually accomplished by air or water spray. In the case of certain steels the radiation and heat flow to the mass of cold steel below the surface is sufficient to harden the teeth of the gear. As an example of the operation of this

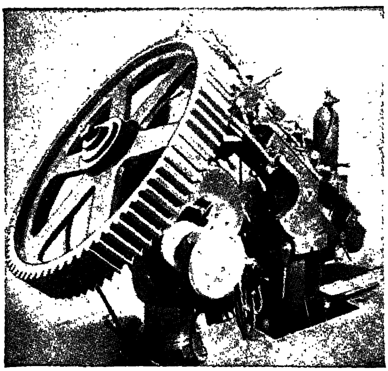


Figure 136. Gleason surface-hardening machine set up for hardening the teeth of a large spur gear.

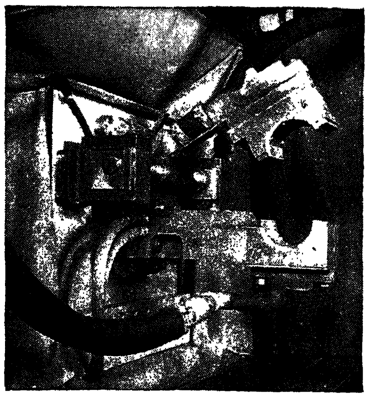


Figure 137. Machine for surface hardening localized areas.

machine, a gear with 90 teeth, 2.37 diametral pitch, and a face length of 5.5 in may be hardened in about 2.6 minutes, with a consumption of about 100 cu ft of acetylene and an equal amount of oxygen. Similarly, a gear of 65 teeth, 3.25 diametral pitch, and 3.5 in of face length may be hardened in about 1.5 minutes, with a consumption of about 26 cu ft of acetylene.

Another machine for surface hardening localized areas is illustrated in Figure 137 and Figure 138. The first illustration shows the machine and the second illustration shows the method of operation. The heat is applied electrically to the surface by induction, and the quenching medium is applied through the same head portion around the work. It is claimed that

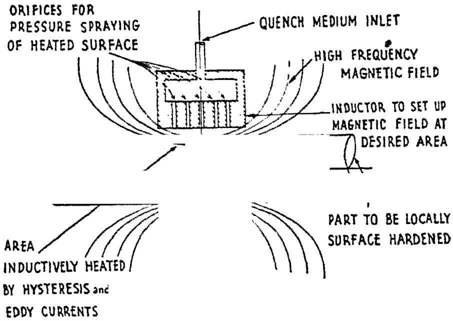



Figure 138. Method of operation for surface hardening localized areas.

the depth of hardening obtained by such a process is greater than that possible where the piece is heated throughout, because the cold core makes the critical cooling rate effective to a greater depth.

Another machine is built for surface hardening the internal surface of cylinders to a predetermined depth. The heating is accomplished by induction, and the machine consists essentially of a fixture to receive the cylinder, a sliding core transformer, a heat head attached to the end of the core, and a quenching head. The process is applicable to cylinders over 1 in diameter, and sizes up to 50 in diameter are under consideration. On long pieces progressive hardening is accomplished by moving the heads at a controlled rate through the cylinder, which is usually rotated to insure uniformity of hardening. Hardening by this method may be accomplished in from 5 to 10 seconds; this short time reduces difficulties from oxidation, grain growth, and distortion.

# Chapter 6

## Alloys and Refractories

In the author's previous book, the subject of the design and application of both alloy and refractory parts of furnaces was discussed, and it is not his intention to repeat this information here. However, in the intervening time (since 1928) there have been numerous improvements in alloys and refractories, and it is of interest and value to review these changes for those who are concerned with the tools used for the heating of steel.

The outstanding change in the use of alloys in the last seventeen years has been the increasing use of the metals, assisted by more exact knowledge of their physical properties and performance under various furnace conditions. The outstanding development in refractories for the same period is probably the introduction of light refractories (insulating firebrick), already discussed in Chapter 4. The discussion in this chapter will be devoted to the mechanical supporting of refractories, which is another important development.

### Heat-resisting Alloys

The principal modern uses for alloys in industrial furnaces are for conveyors of all kinds, radiant heating tubes and muffles, and for recuperators.

**Furnace Conveyors.** In common with ordinary conveyor design, the wide variety of products to be handled by furnace conveyors constitutes the major problem. There are many additional complications, however, which are peculiar to furnace conveyors alone, and which limit the number of satisfactory devices. These complications include the effect of temperature, interference with proper application of heat in the furnace, and difficulties with the proper support and maintenance of the mechanism when totally enclosed in the hot furnace structure. The various designs of furnace conveyors to be described may be divided conveniently into the following classes:

(1) Rails in many different forms.
(2) Chain conveyors.
(3) Belt conveyors.
(4) Roller hearths.
(5) Walking beams.
(6) Rotary hearths.

(7) Car bottoms.
(8) Batch furnaces with external handling.
(9) Miscellaneous forms.

*Water-cooled Rails.* This type of rail is commonly used in high-temperature furnaces, such as those for the heating of steel slabs and billets. They are usually supported on refractory piers, although in some underfired designs they are held up by water-cooled beams and posts. Wherever possible, standard pipe sections are used for simplicity and cheapness, and a steel bar is often welded to the pipe to serve as a wearing strip and to separate the product to some extent from the cold pipe.

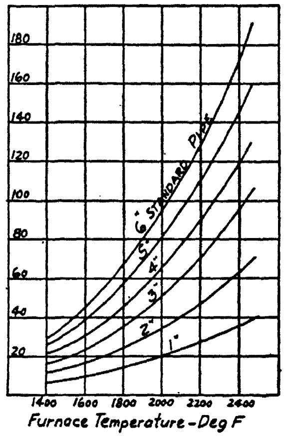



Figure 139. Heat losses in furnaces due to absorption of heat by water-cooled pipes of several standard sizes when exposed to various furnace temperatures.

The principal objection to water-cooled rails is their absorption of heat. The amount of this absorption depends upon the furnace temperature and the area of the water-cooled surface, and the numerical value may be calculated from the data of Figure 139, which shows the absorption of heat by water-cooled pipes of several standard sizes when exposed to various furnace temperatures. In all cases it is assumed that the entire area of the pipe is exposed, so that in cases where the pipe is imbedded in refractory or otherwise protected, the amount of heat will be reduced in proportion to the amount of total area exposed. In determining the losses resulting from water-cooling it must be remembered that the actual heat required in the fuel to offset the absorption will be the values in Figure 139 divided by the thermal efficiency of the furnace. For example, if the furnace temperature is 2000 deg F, the thermal efficiency without recuperation is 50 per cent and the heat input to offset heat absorption will be twice the values of Figure 139.

*Alloy Rails.* Rails of heat-resisting metal may be divided into two classes: (1) "dry rails" with sliding friction, and (2) roller rails. The first class comprises all kinds of rails on which the material or the loaded pans

or trays slide directly on the rails. Such rails are usually of an alloy containing between 10 and 15 per cent chromium with 25 to 35 per cent nickel, or of an alloy containing between 24 and 28 per cent chromium with 10 to 12 per cent nickel, and may be used for temperatures up to about 2000 deg F with satisfactory life. Rail sections are of many forms designed to afford maximum strength with minimum weight, and the metal thickness is from $\frac{3}{8}$ to $\frac{5}{8}$ inch, care being taken to avoid abrupt changes in metal section which will cause cracking of the metal. Necessary allowance must be made for expansion in the design of any alloy parts. With dry push skid rails it is customary to use a coefficient of sliding friction of 100 per cent of the weight pushed, because of the tendency to sticking between the hot rail and the charge.

To reduce friction, particularly in long furnaces with heavy loads, roller rails such as that shown in Figure 140 are used. These rails are of U section and are cast with trunnions to receive the cast rollers. The surfaces

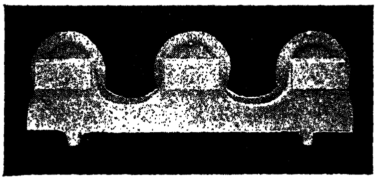


Figure 140. Roller rails used for carrying trays of material or carburizing boxes through a furnace. An innovation here is the use of replaceable journal boxes.

are not machined, because the cast skin resists wear better than a machined alloy surface, so that the foundry practice is important in the casting of these rails and rollers. The centers of the rollers are set so that a minimum of three rollers of each rail are under the tray or box at all times.

In most furnace designs the prorated live load on any one roller seldom exceeds 50 lbs, and the maximum for long roller life is 75 lbs for a standard roller. With this maximum load the amount of wear on either the alloy roller or the rail trunnion is remarkably small, and the rails and rollers will last for years in most applications for annealing and heat treating. Greater loads will shorten the life of the rails, but loads as high as 150 lbs per roller have been applied on roller rails.

Table 34. Allowable Stress for Stationary Beam Sections of 35 Ni/15 Cr and 25 Cr/12 Ni Heat-resisting Alloys

| Furnace temperature (deg F) | Allowable stress (lbs/sq in) |
|---|---|
| 1400 | 1500 |
| 1500 | 1100 |
| 1600 | 750 |
| 1700 | 500 |
| 1800 | 300 |
| 1900 | 150 |
| 2000 | 100 |

The strength of the alloy metal decreases rapidly with increase in working temperature; and this fact must be understood if serious and expensive trouble is to be avoided. In calculating the strength of any stationary beam section of alloy by the usual formulas for loaded beams, the allowable stresses shown in Table 34 should not be exceeded if a gradual deformation of the section is to be avoided.

These values in Table 34 are for average alloys and include safety factors to cover all ordinary contingencies. Creep-test values are somewhat higher. In Figure 141 are shown creep-test curves for a chrome-nickel-molybdenum

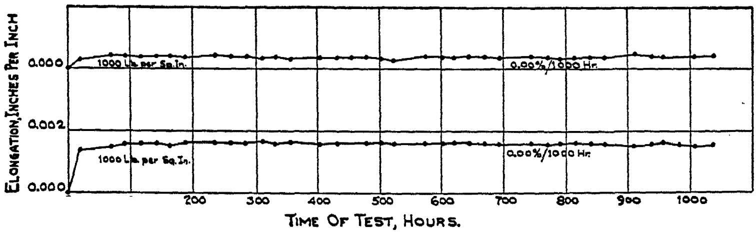



Figure 141. Creep-test curves for a chrome-nickel-molybdenum alloy at 1000 lbs per sq in stress at 1850 deg F.

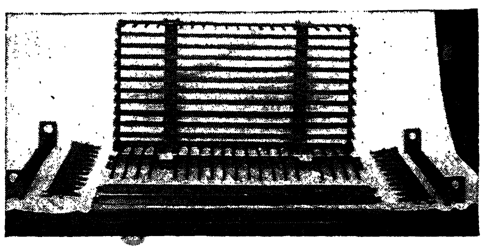
alloy at 1000 lbs per sq in stress and a temperature of 1850 deg F, and it will be noted that there is no permanent deformation beyond that occurring in what is known as the initial stage of creep in the first 100 or 200 hours.

*Carrier Shoes and Trays.* Where the heated material cannot be pushed directly on the rails, carrier shoes or trays are employed. The labor requirement for carrying these trays back to the loading end of the furnace is objectionable, but there are many cases in which this is more economical than a more automatic device.

Shoes are used where the product will span between rails, as in the case of crank shafts. Trays are used for smaller parts and are made of light-alloy section, cored as much as possible and carefully designed to avoid cracking and warping.

Figure 142 shows an assembled tray of novel design for a roller rail furnace. The bottom is made in a series of separate pieces which are small

Figure 142. Conveyor tray for roller rail furnaces, in which the tray is constructed of individual pieces of light section to reduce difficulties from expansion. The push is taken by the heavier longitudinal I-beam sections only.



I-beams with $\frac{1}{4}$-in metal thickness. The sides and ends are separate pieces with connecting pins. This design not only eliminates strains due to unequal expansion, but the use of I-beams for the bottom bars permits heavy loads to be pushed on two lines of roller rails without the necessity for a heavy overall tray weight.

A hinged tray to save weight by insuring more uniform stresses where more than two roller rails are involved is shown in Figure 143. Variations in levels of three roller rails will not stress the hinged tray shown in the illustration because it will accommodate itself to the rail levels. The design also reduces the size of the individual alloy pieces, which is the aim of an alloy designer, since smaller pieces have less tendency to warp. A variation in the use of the hinged tray is a smooth tube conveyor which has

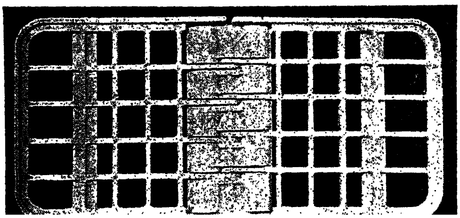


Figure 143. Hinged tray for use in annealing, carburizing or heat-treating furnaces.

been developed to remove all compression between trays and to permit one tray to be sent through the furnace at a time if desired. The conveyor consists of a tube about 6 inches in diameter extending lengthwise through the furnace and supported by conventional grindstone roller bearings. Parallel to this tube on either side of the furnace is a roller rail. The hinged tray is supported at the center by means of rollers on the bottom of the tray which rest at a slight angle on the smooth tube conveyor. The tray is propelled through the furnace by the friction drive of the angulated rollers on the bottom of the tray against the rotating tube.

Trays are applied in many different ways, including automatic dumping where lugs on the sides of the tray engage stationary fixtures in the furnace and allow the tray to swing down and discharge its contents into a suitable chute.

*Chain Conveyors.* The simplest form of chain conveyor is that with which the product rides through the furnace on several strands of alloy chain. In spite of its simplicity, however, the chain conveyor can be one of the most troublesome of all furnace devices unless it is properly proportioned and correctly applied. The reason for this is that if the chain is even slightly overloaded it will gradually elongate and the pitch of the chain will change. When this occurs, the chain tends to climb on the sprockets, enormous stresses are set up, and the point of failure approaches rapidly. By assuming a friction coefficient of 100 per cent and by using

the allowable stresses given in Table 34, such difficulties can be effectively prevented.

Figure 144 shows a typical cast alloy chain link arrangement, while Figure 145 shows a forged alloy chain. There are many possible designs, including side links and pins, but in all cases sufficient metal area must

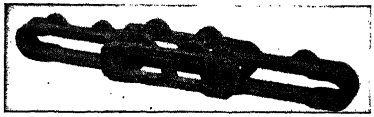


Figure 144. Cast alloy chain links.

be provided, regardless of cost, to keep the unit stresses below the maximum allowable value for the furnace temperature in any case. Figure 146 is a typical large alloy sprocket for use where the chain is to be returned inside the furnace, or where the work must be discharged from the chain inside the furnace.

The majority of chain conveyors are driven from the head end, with idler drums turning freely and independently on the tail shaft, which is

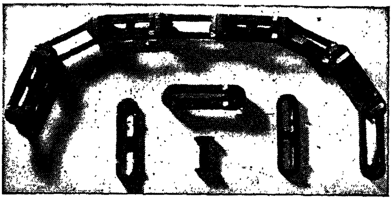


Figure 145. Forged alloy chain links.

mounted on a trunnion and provided with a counterweight to take up expansion of the chain. Chain strands are guided through the furnace by alloy rails or troughs and are generally returned on a structural channel under the furnace, although an internal return arrangement is sometimes provided to reduce heat losses from the chain. Where the furnace length exceeds about 30 feet it is advisable to consider driving the chain at both ends, in which case the tail-shaft drive is connected to the head shaft by

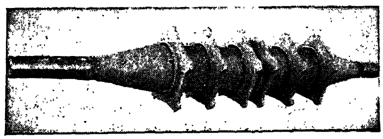


Figure 146. Sand cast alloy shaft with sprockets for conveyor chain.

means of a slip clutch and has only sufficient strength to take care of the chain return under the furnace. The tail shaft must be mounted on a trunnion in this case also, in order to take care of expansion of the chain.

In some applications, the chain does not carry the material but is provided with fixtures which project above the carrying rails in the furnace

and slide or roll the material through the furnace on these rails. In other instances, fixtures are provided on the chain to carry the product with minimum contact, as in the case of furnaces to carry sheet products, where

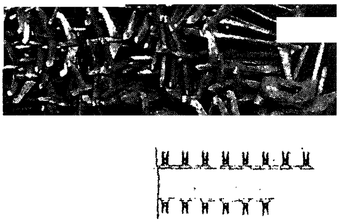


Figure 147. Alloy carrier blades for conveying sheet products. Inset shows method of fastening alloy blade to chain. Lower view shows conveyor arrangement.

the fingers are sometimes provided with porcelain tips to reduce the danger of spoiling the surface of the sheets. Figure 147 shows an example of a chain provided with fingers.

Before the use of alloy metal became general in furnace construction, external chains of steel or malleable iron with replaceable fingers projecting through the furnace floor were used, but this design involves a slot which is difficult to seal, and with the increasing importance of atmospheric control in most furnaces the use of this design has been almost abandoned by furnace engineers.

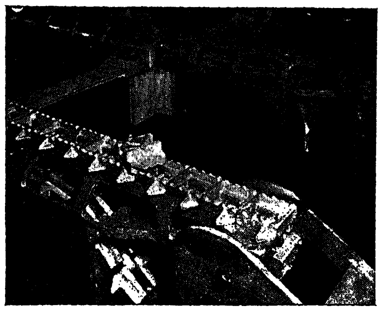


Figure 148. Pusher-type chain conveyor.

A variation in this idea of external chains is the overhead chain of cheap material with alloy hangars projecting through a slot in the furnace roof. The sealing of a roof slot is somewhat more practical, and this design is commonly used in enameling furnaces. It is also used in automotive plants for the handling of various parts to be hardened and drawn.

Another variation of chain arrangement is the so-called pusher chain shown in Figure 148. In this case the chain is made up of conveying shoes, such as were mentioned in the preceding section, which are pushed through the furnace on rails, as shown in the illustration. In this case, however, the shoes are loosely linked together to form a continuous chain so that

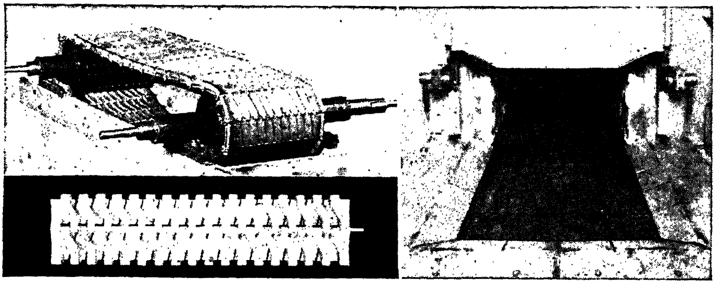


Figure 149. Flexible alloy belt consisting of one-piece spiral link castings which extend the full width of hearth. Lower view shows bottom side of casting, illustrating spiral link design.

they are automatically returned to the loading end of the furnace. The illustration includes a good view of the alloy rails and the flexible attachment of spacer castings used to keep the rails in line in the furnace.

Chain belts, made up of a large number of small alloy castings, are a major development in furnace design in recent years, and are widely used for handling a variety of small parts without trays, such as bolts. The

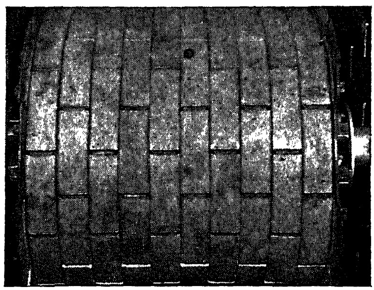


Figure 150. Belt consisting of cast alloy links joined together with flat cast alloy pins.

alloy links are joined by alloy pins to form a flexible belt which passes over metal drums. In order to conserve heat and because most of the material handled is to be quenched without any temperature drop, the drum at the discharge end is usually of alloy and enclosed within the furnace. The chain return in this case is also enclosed within the furnace. The drive may be at either one or both ends and may be of either chain or ratchet type.

Another link design, in which each link is in one flexible piece across the width of the furnace, is shown in Figure 149. Another variation is given in Figure 150, where flat cast alloy pins are used to join the sections.

A light belt design is shown in Figure 151. The belt is made of stampings from 16-gage alloy sheet and is intended for light material at comparatively low temperatures under 1400 deg F. The drum is moved by a ratchet drive as shown in the illustration.

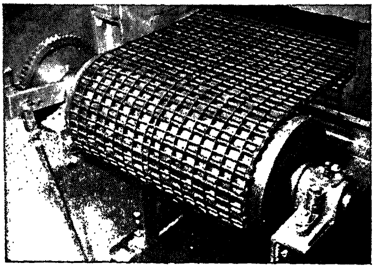


Figure 151. Open design of belt constructed from alloy sheet stampings joined with alloy steel cross rods and tube spacers.

Still another arrangement of chain conveyor is the flight type of Figure 152. In this design alloy slats are fastened to strands of chain, the slats being arranged with holes to permit circulation of heat around the product. For tempering furnaces at low temperatures, rolled alloy in light sections may be used to good advantage.

*Wire Belt Conveyors.* Another important development in furnace design is the woven-wire alloy belt which has been rapidly improved to a point

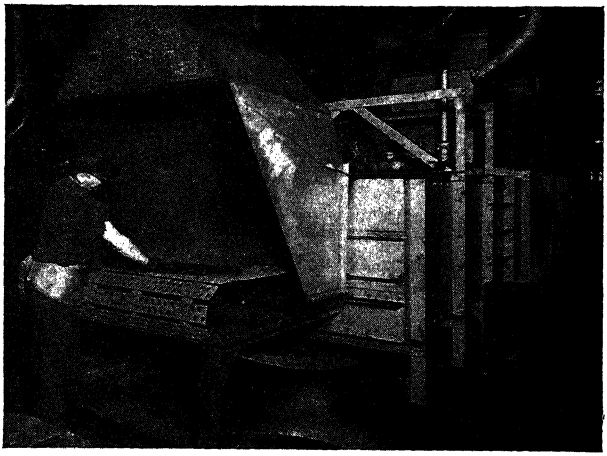


Figure 152. Furnace equipped with chain conveyor having perforated alloy slats fastened to strands of chain.

where it is an ideal application for many uses, particularly where the temperature does not exceed 1750 deg F or where a bright-annealing atmosphere is used, which preserves the small wire sections from which the belts are made. An established use of woven-wire belts is in copper-brazing furnaces operated at a temperature of 2100 deg F with protective atmosphere.

These belts are carried on steel pulleys, with one end on counterweighted trunnions to allow for expansion. A counterweighted steel hugger roll is usually used at one of the pulleys to press the belt against the face of the pulley and produce the necessary driving friction. The principal problem solved in the development of these belts was the tendency to stretch when subjected to tensile stress while hot. Designs now available have a long

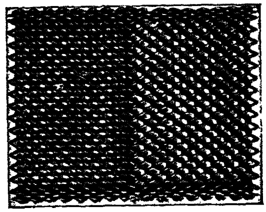


Figure 153. Woven spiral wire belt with special selvage edge and straight wires across the belt at intervals.

life without excessive stretching. Figure 153 shows a belt designed for this work. One type is a woven spiral belt with special selvage edge and straight wires across the belt at intervals to reinforce it against the lateral contraction under tension. Another type is a balanced spiral weave to insure flatness and true running by balancing the tendency to creep. Both types may be obtained with woven edges to prevent material from falling off the side of the belt.

In still another design of woven-wire belt, every spiral wire hinges upon a reinforcing wire, which wire is bent upon itself to a hairpin formation. This arrangement provides an additional selvage within the usual outer

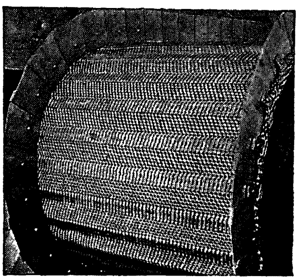


Figure 154. Woven-wire belt with guard edge for retaining material on belt.

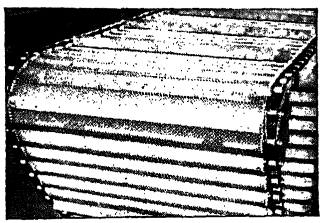


Figure 155. Woven-wire belt with lifts for carrying products at an angle.

selvage of the fabric, to prevent the fabric from fraying or separating in the event that the outer edge becomes torn or damaged. Not only does this style of rod reinforce the belt against lateral contraction, but it also assists in more definitely tying the belt together.

Figures 154 and 155 show furnaces equipped with belts to accomplish specific purposes, such as the provision of a guard edge to retain the mate-

rial on the belt, angle lifts to hold the material while carrying it at an incline, and an arrangement of chain edges for positive sprocket drive at both sides. Figure 156 illustrates an alloy belt pulley for use inside the

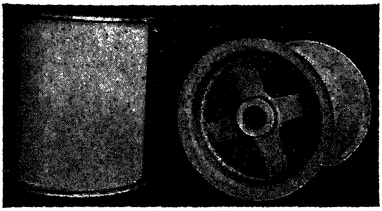


Figure 156. Alloy pulley for use inside of furnace when material must be quickly discharged for quenching.

furnace when the material must be discharged from the belt inside the furnace, as in the case of quenching for hardening.

*Roller Hearths.* The roller type of hearth is of increasing importance in furnace design and has reached a high degree of mechanical perfection. The advantages of this type of conveyor include:

(1) Moving parts outside the furnace and available for inspection and lubrication.
(2) Trays, shoes, or pans not required for most materials.
(3) No heat lost by the conveyor.
(4) Conveyor does not interfere with the best methods of heat application.
(5) Openings can be sealed for bright-annealing applications.
(6) Discharge can be increased in speed without affecting the remainder of the furnace by use of separate drive for rollers.
(7) Rollers can be replaced without interfering with furnace operation.

In the design of alloy rollers for these furnaces it has been found that if the continuous movement of the rollers is insured, the allowable stresses may be greater than in the case of the stationary parts already discussed and specified in Table 34. Table 35 is a similar summary of allowable stresses for moving alloy rollers.

Table 35. Allowable Stresses for Moving Heat-resisting Alloy Rollers

| Furnace temperature (deg F) | Allowable stress (lbs/sq in) |
|---|---|
| 1400 | 2800 |
| 1500 | 2600 |
| 1600 | 2200 |
| 1700 | 1700 |
| 1800 | 1200 |
| 1900 | 700 |
| 2000 | 200 |

These figures are used in the usual formulas for beams, and the roller section used is usually a hollow tube, except in the case of small rollers under $1\frac{1}{2}$ inches in diameter.

Self-aligning bearings are frequently used on the outside of the furnace, preferably mounted separate from the furnace shell to avoid difficulties from expansion. The rollers pass through blocks of soft refractory in the furnace lining and are sealed outside the shell by means of plates with springs, bushings, or some other device.

The rollers may be driven by means of ratchets, chains, or bevel gears on a line shaft, and, as already stated, may be divided into separate groups with independent drives.

The steel mills have developed a number of different roller-hearth applications of considerable interest and importance for the handling of sheet

Figure 157. Alloy dry shaft with discs upon which heated product is carried through the furnace.

products. Some of these rollers are water-cooled, but the majority are dry-shaft rollers of alloy. A typical dry roller with discs upon which the sheets travel is shown in Figure 157. Still another centrifugally cast roller with welded necks is shown in Figure 158; a portion has been cut away in this case to show the perfection of the welded joint. The rollers in this illustration are used in a furnace for annealing billets from 2 to 8 inches

Figure 158. Centrifugally cast dry shaft with welded necks. Portion cut away to show welded joint.

thick which cover the hearth almost solidly, which will afford some idea of the possibilities with moving alloy rolls.

A novel method of attaching end trunnions is illustrated in Figure 159. The trunnion is funnel-shaped and fits the inside of the cylindrical body of the hollow roller. The roller is slotted at the ends and is swedged over the trunnion, after which all seams are electric-welded to form a construction of great strength.

The alloy used in furnace rollers is usually a combination of 25 to 35 per cent nickel with 10 to 15 per cent chrome, except in cases of sulfurous

fuels, when an alloy of 25 to 30 per cent chrome and 10 to 12 per cent nickel is used to withstand the corrosive action of the sulfur.

A special design comprises a centrifugally cast shaft with loose ends for the bearings; this shaft is used for conveying sheets through a furnace for normalizing. With the increased width of sheet furnaces the diameter and cost of alloy rollers have increased, so that methods have been developed to reduce the stresses in the rolls by reducing the unsupported spans.

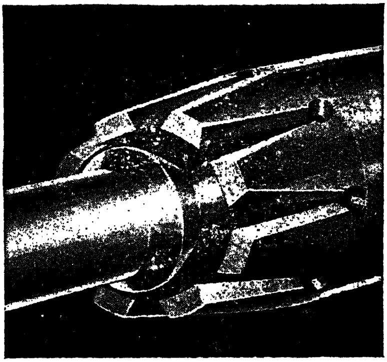


Figure 159. Method of attaching end trunnions to cylindrical body of hollow roller.

One method for reducing roller diameter is to provide alloy rollers in the furnace to support the shaft at several points. The supporting rollers are similar to those of the roller rails already described and are supported on alloy trunnions usually carried directly by the steel binding of the furnace bottom. Figure 160 shows the cross-section of a wide furnace arranged in this manner, and Figure 161 shows a roller bottom assembly in such a furnace 9 ft wide inside.

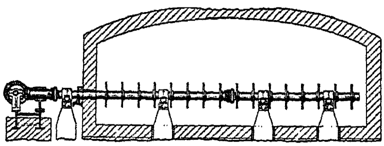


Figure 160. Cross-section of a wide furnace with rollers supported at three points in the furnace.

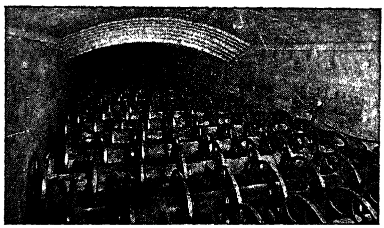


Figure 161. Roller shafts in this 9 ft wide furnace are supported by roller bearings inside the furnace.

Rollers are used for other purposes in furnaces, including cantilever rollers for charging and discharging tubes and bar products in furnaces, and roller shafts for continuously rotating a heated product while in a batch-type furnace.

*Walking Beams.* The walking-beam type of furnace conveyor mechanism consists in all cases of two sets of supporting beams in a furnace, one stationary and one movable, or both movable. In the former type the movable beams lift the material and carry it forward to set it again on the stationary beams, which support it while the movable beams are returning to their original position at a level below the supporting beams. In the second type one set of rails has vertical motion to lift the charge, while the second set of rails has only horizontal motion, and the charge rests on them only during the forward stroke. The speed of travel is regulated by the stroke and frequency of lift.

Early furnaces of this type (still used for heavy loads) consist of refractory beams riding on rollers carried on movable arms projecting through the bottom of the furnace. The lifting motion of the roller arms and the

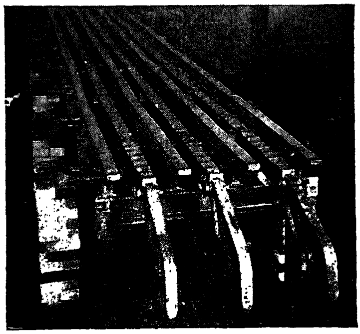


Figure 162. Assembly of walking-beam conveyor mechanism showing alloy stationary and moving beams.

horizontal travel of the beams on the rollers are separate actions. More recent furnaces have alloy beams of relatively light design and the lifting and traversing action of the beams are interlocked, either by mechanical or electrical means. Figure 162 shows an assembly of stationary and movable beams. The top surface of all beams is cast with ridges to prevent rolling when handling round products through the furnace.

In the design of these furnaces it is essential that the stresses be kept low in the beams and supports, and that ample provision be made for expansion. It is also necessary that the beams be spaced close enough together so that the heated product will not sag between the beams.

*Rotary Hearths.* Rotary hearths involve a circular furnace chamber with a rotating floor, and are ideal for handling many chunky products and for high temperatures. The hearth ordinarily remains within the furnace and therefore does not lose heat. Trays or other containers are not required, and the construction can be designed without the use of alloy, to permit the use of such furnaces at temperatures high enough for forging and forming operations.

The furnace chamber may be circular with a solid circular hearth, or a center wall may be provided, with the circular hearth in "doughnut" form around the center wall. In either case a steel framework with cast-iron retaining edges is provided to retain the refractory bottom, and the

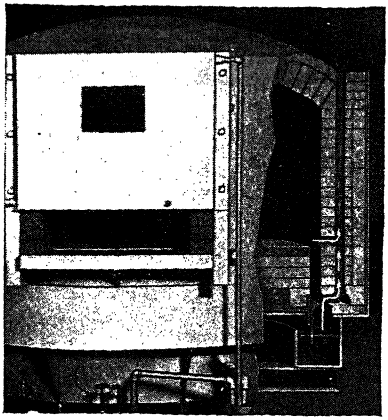


Figure 163. Cut-away view of rotary hearth furnace to show arrangement of water seal and vents.

hearth is supported by wheels with roller bearings and running on a circular track. A circular rack under the frame is engaged by a pinion driven at desired speed.

The heated product may be supported on the hearth by a variety of means. For high temperatures the product is usually charged directly on the refractory bottom. The opening between the hearth and the wall is usually sealed by sand, but in the furnace of Figure 163, water is used for the sealing medium. The furnace in this illustration is designed for forging or for heat-treating.

For heat-treating of steel parts, these parts are usually supported above the refractory bottom on alloy supports. Figure 164 shows a very large alloy hearth for a rotary furnace, where the hearth plates are made in sections and supported by means of alloy posts which are long enough to

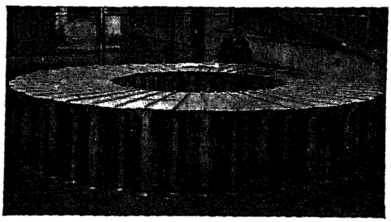


Figure 164. Large alloy hearth for rotary furnace showing hearth plates made in sections and supported by means of alloy posts.

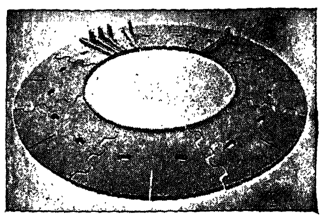


Figure 165. Alloy hearth for rotary furnace made in sections with slots provided for expansion.

extend to the structural bottom frame to keep the hearth in perfect alignment. Figure 165 shows another hearth for a rotary furnace, which is made in sections with slots provided for expansion. Fixtures are shown on the hearth for holding the product while it passes through the furnace for heat treatment.

A number of furnaces have been built in which the sections of the hearth were individually hinged, so that they could be tilted at the discharge door to discharge the product to an enclosed chute for quenching. As such designs are necessarily complicated and likely to give trouble in operation, manual quenching without the automatic features is generally more economical in rotary furnaces.

Another variation in rotary-furnace design consists of an alloy spindle rotating with an alloy center post and carrying alloy arms from which the heated product is suspended by suitable alloy hangars. The post may rest on a thrust bearing and be guided by outside roller bearings at the top and bottom.

*Car Bottom and Batch Furnaces.* In the ceramic industry the car bottom kiln is used almost exclusively for continuous handling, although the walking-beam mechanism has been successfully applied. The construction of the cars is similar to that of the rotary hearths described, and the product is generally supported above the car bottom to allow heat circulation, the supports being either refractory piers or alloy fixtures. At the ends of the kiln, the cars run onto a transfer car which transfers them to a parallel return track outside the kiln.

The line of cars is usually moved by an oil-hydraulic system which may either push a full car length at each stroke or gradually move the cars continuously at a regulated speed, in order to insure a very gradual change in temperature as the cars pass through the different zones in the kiln.

The same design has been found useful for a number of applications in steel mills, such as the annealing of coils of stainless-steel rods and of sheets in piles.

A continuous arrangement with many advantages consists of a series of car-type furnaces served by some form of mechanical handling mechanism outside the furnace. The fronts of the furnaces are arranged in line and the handling means effectively ties the series of furnaces together to form a continuous producing unit. The principal advantages are:

(1) Simplicity, with no moving parts in the furnace.
(2) Flexibility, with the number of furnaces operating varied to suit requirements.
(3) Economy, since all units are at all times at maximum capacity.
(4) Maintenance, low because machinery is at all times available for repair.

Figure 166 shows a typical arrangement of nine car-type furnaces with handling crane, which is provided with lifting fingers to fit between the piers on the cars and rapidly lift the charge from them to the storage racks. The cars are charged in the same manner. A feature of importance to such installations is the motor-driven car puller on each car, consisting

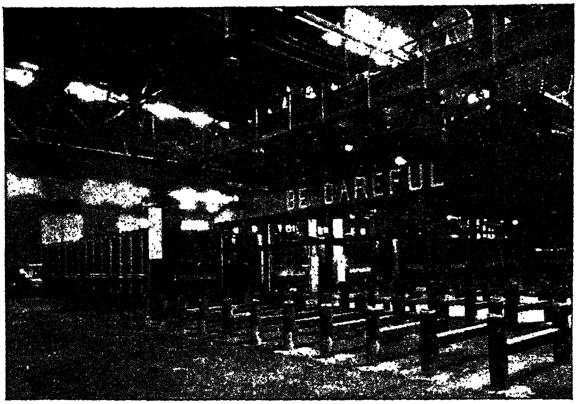



Figure 166. Arrangement of car furnaces with handling crane provided with lifting bars to fit between the piers of cars and rapidly lift charge from cars to storage racks.

of a rack under each car and a motor-driven pinion for rapidly moving the car in and out of the furnace. With this arrangement the charge in any furnace can be replaced in a total time of three minutes, so that the operation of the furnaces is practically continuous. Gantry-type cranes may also be used in conjunction with car furnaces in the same manner, as shown in Figure 111.

Batch-type hearth furnaces may be arranged similarly, but in this case the handling machine must enter the furnace to charge and discharge the load on the hearth. Figure 112 shows one of a series of furnaces arranged with longitudinal piers for supporting the charge and served by a crane equipped with prongs to enter the furnace between the piers and lift the charge. A similar arrangement may be made for handling small parts in alloy trays.

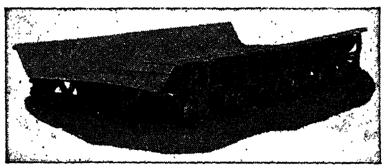


Figure 167. Comparatively light-weight furnace cars constructed entirely of heat-resisting alloys.

Comparatively light-weight cars constructed entirely of heat-resisting alloy, as shown in Figure 167, have been used in some installations, but in this case the entire car must be heated to temperature and the repeated heating and cooling of the car requires great care in its design and construction.

Enameling furnaces served by speed forks represent another example of batch furnaces with external handling. Because the charge is very light in such applications, these forks are usually hand-operated. Figure 168 shows a typical installation.

For heavy pieces, such as billets for rolling and the like, a motor-driven machine is made to handle the pieces to and from the furnace. Such a machine may be supplied with electric current through a flexible cable and reel. Heavier machines operating on rails are also made for very heavy

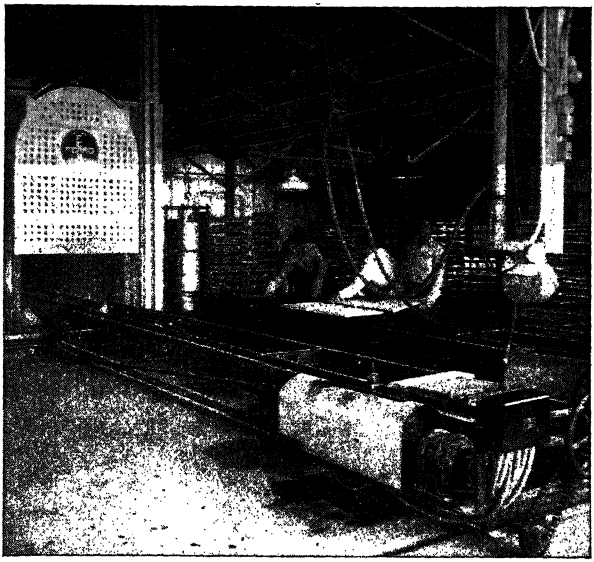


Figure 168. Charging forks of heat-resisting alloy are used in connection with porcelain enameling furnaces.

service. (See Figure 199 in Chapter 7.) One machine of either type will handle (both loading and unloading) up to about 80 pieces per hour in a properly arranged group of batch furnaces with receiving and loading tables in proper relation to the furnaces.

*Shaker Hearths.* For handling small pieces the shaker or reciprocating hearth has frequently been used, as illustrated in Figure 169. In this design the reciprocating movement is accomplished by means of a cam in conjunction with a spring, which causes a short, rapid movement of the hearth. The speed of the product sliding on the hearth can be regulated by the frequency of the stroke. The principle is based upon inertia, which causes the product to advance by its own momentum when the hearth is suddenly stopped at the end of each forward stroke.

Such furnaces may be open-fired or arranged with a muffle, as shown in Figure 169. A special sealing device is provided at the discharge end

of this furnace for quenching the product without contact with the outside air. The design is simple and operates without trays or conveying mechanism to cause trouble or carry heat from the furnace. By utilizing the muffle arrangement, protective atmospheres may be applied to this type of furnace in small sizes as limited by the practical size of the muffle.

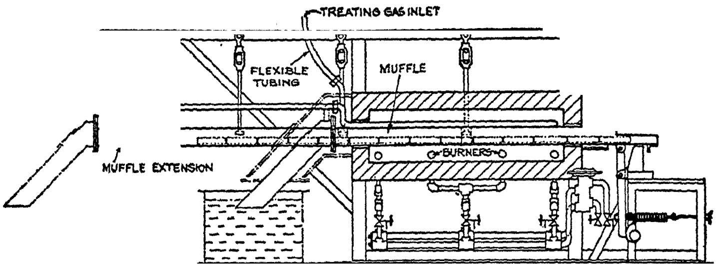



Figure 169. Cross-sectional view of shaker hearth or reciprocating hearth furnace, illustrating construction of hearth.

*Rotary Muffles.* This type of furnace for small parts consists of an alloy cylinder through which the work travels; screw-type vanes are usually applied on the inside of the cylinder to control the movement of the product. Parts of various sizes and shapes may be handled in this type of furnace, as well as material in powder form for special applications. The product to be heated is fed into the retort from a hopper by means of a cup which charges a measured quantity through a central chute into the retort. The hopper holds a supply of parts sufficient for 15 or 20 minutes, to reduce the amount of labor required. The material is discharged through a port at the discharge end of the machine.

The retort arrangement permits the use of protective or carburizing gases, as desired, and since the retort remains in the machine, the thermal efficiency is high. Rotation of the retort insures mixing and uniformity,

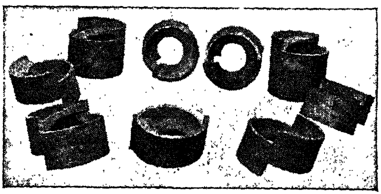


Figure 170. Alloy parts which when assembled form a tube with an internal spiral for conveying parts being heat-treated.

and the amount of labor is relatively low. Maintenance is reduced by the fact that all moving parts are outside the furnace, but the alloy retort must occasionally be replaced.

Figure 170 shows parts of a furnace which, when assembled, form a tube with an internal spiral for conveying small pieces, such as lock washers, bolts, and so forth, to be heat-treated.

*Vertical Furnaces.* A number of vertical furnaces have been built for special applications. Included in this classification are vertical strip furnaces in which the metal strip passes over a roller at the top of a vertical chamber, and vertical chain furnaces where the chains pass over a head sprocket and carry fixtures for supporting the product in a suspended position during the travel through the furnace.

This concludes the discussion of the many different forms of handling devices which are constructed of alloy metal and which have been devised and successfully applied to the handling of material of all sizes and shapes through heating furnaces.

**Radiant Tubes.** With the introduction of protective gas atmospheres to control scaling and decarburization, the radiant-tube heating element was developed to compete with electrically heated furnaces or with fuel-fired muffle furnaces; and this has developed into an important use of heat-resisting alloy in both cast and rolled forms. These tubes muffle the flame from the furnace interior (in contrast to muffling the heated material from the flame) and radiate heat to the furnace in exactly the same manner as electric heating elements. They are usually 4 or 5 inches in diameter; this range of sizes has been developed as the best combination of strength with radiating area for a thin-walled tube, and the limiting hot length (inside furnace width) is about 6 ft. For most applications the maximum furnace temperature for tube firing is 1600 deg F, which is fixed by a maximum safe tube temperature of about 1850 deg F. Under these conditions, the maximum allowable heat radiation from the exposed tube is about 40 Btu per sq in of tube per hour. Since, at these temperatures approximately 40 per cent of the heat input leaves the tube as sensible heat in the waste gases, the amount to be radiated is about 60 per cent of the heat input. Thus the maximum allowable heat input per sq in of tube surface in the furnace is about 67 Btu per hour. The input ratings of several tube sizes in Btu per hour is then:

| Diameter | Length of tube inside of furnace | | | |
|---|---|---|---|---|
| (in) | 36 in | 48 in | 60 in | 72 in |
| 4 | 30,000 | 40,000 | 50,000 | 60,000 |
| $4\frac{1}{2}$ | 34,000 | 45,000 | 56,000 | 68,000 |
| 5 | 37,500 | 50,000 | 62,500 | 75,000 |

The tubes are made from fabricated alloy sheets with welded seams. Since the usual reason for using radiant tubes is to permit the use of protective atmospheres in the furnace, it is necessary to seal the tubes through the furnace walls. This is usually accomplished by a gasketed flange against the furnace shell at the discharge end of the tube. The tube expands through an opening in the wall at the burner end. The burner is mounted on the end of the tube and the assembly is surrounded by a gasketed box

outside the furnace. Gas and air connections to the burner are made with flexible hose to permit expansion of the tube and consequent movement of the burner.

The number of tubes is determined by the heat requirements in the furnace, and horizontal tubes in continuous and box-type furnaces may be located above and below the material to be heated. A space of at least two tube diameters is left between tubes to prevent interference with the radiation from the tubes to the work. In many furnaces the tubes are in a vertical position, as shown in Figure 219.

## Furnace Refractories

The author's previous book described the refractory combinations commonly used in industrial furnaces, and these descriptions need not be repeated here. However, the subject of mechanically supported refractories has not been previously discussed and it is of sufficient interest and value to merit consideration. As such designs are used in special applications, a description of some of them will give the furnace designer and user a guide in other applications to suit his needs.

In the more standardized field of boiler design, the use of mechanically supported refractories has been highly perfected, and the designer of heating furnaces will find that many of the standard boiler furnace designs can be used to advantage in the solution of his problems. For that reason, both walls and arches have been included in this discussion.

**Suspended Arches.** The fundamental considerations involved in a study of suspended roofs or arches are simplicity, flexibility, strength, tightness, insulating value, and maintenance; and a better idea of relative merits can be obtained by examination on the basis of these requirements. Flexibility means the adaptability of the suspension means to the various roof contours required in practice, particularly nose arch constructions. The quality of tightness in suspended roofs assumes more importance as the necessity for controlling atmospheres in heating furnaces increases. The insulating value of any suspended roof depends upon the effective thickness of refractory between the heated surface and the suspension hangers, and also upon the proportion of total area which may be effectively covered with insulation if desired. Maintenance involves the resistance of the arch to damage from thermal shocks and the ease of replacement of damaged tile.

Figure 171 shows one form of suspended arch and illustrates the nose construction as well as the flat roof. The design is simple, in that the tile are directly connected to standard supporting I-beams by means of a small casting for each tile, which permits the easy removal of each tile as a separate unit. A feature of the design is that the tile are of such shape that complete interlocking is effected, as shown in the illustration. The design forms a wedge which locks each tile throughout its length and prevents any

cracked portion of a tile from falling out. With this design a high percentage of total area may be insulated if desired.

Another type of suspended arch is illustrated in Figure 172. In this design alternate rows of tile are suspended directly from double channels,

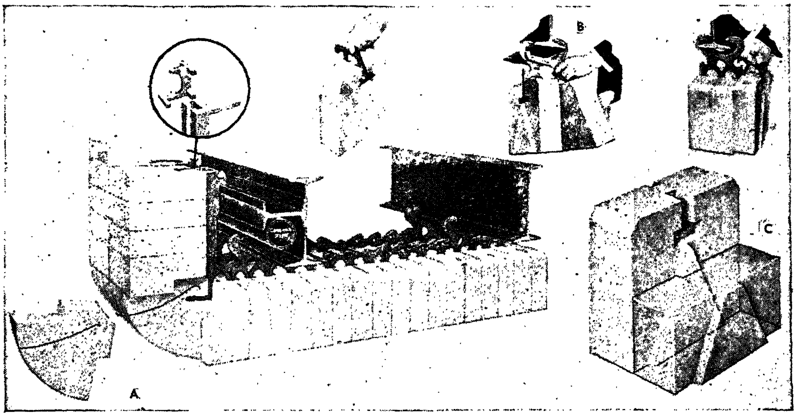


Figure 171. (A) Illustrating construction of arch and interlocking of nose. (B) Method of supporting tile. (C) Cutaway view of interlocking tile.

while the intermediate tile are held by the supported tile without any other connection to the supporting structure. These intermediate tile are readily removable, and the bottom flanges of the supporting channels are notched at intervals so that the supported tile may be removed. With this design the total area may be insulated if desired. In the nose construction for this

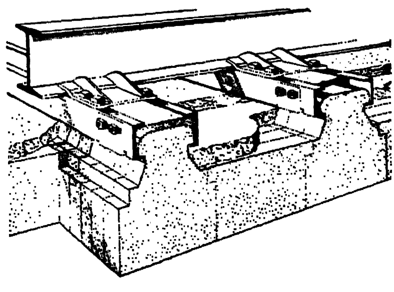


Figure 172. Channel supported arch, showing application of insulation.

type of arch, the radial tile are individually held by clips which are fastened to the supporting casting.

Figure 173 shows an arch which utilizes small tile, corrugated on all four sides. The purpose of the corrugation is to form a seal against gas leakage or air infiltration, and to prevent the bonding material from fusing out of the joints. The use of small tile is of advantage in reducing spalling. In this design the tile are directly supported on heat-resisting metal castings

which are in turn hung from the structural steel framework. The structure is so arranged that flexibility of the adjustment of the hangers is provided.

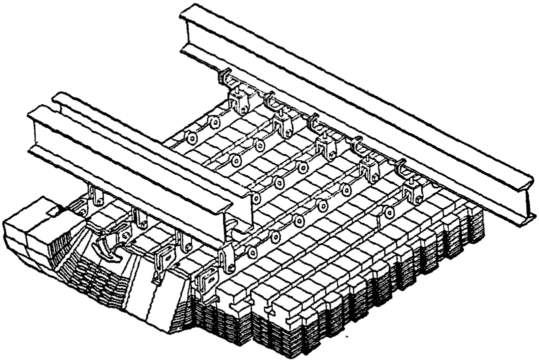


Figure 173. Nose construction utilizing small radial corrugated tile held by clips to the nose casting.

Another suspended arch is illustrated in Figure 174, which shows both the horizontal arch and the nose construction. A feature of this design is that every tile hangs perpendicularly in all sloping sections and nose constructions, as well as in the flat sections of the arch, so that the tile cannot slip or twist. The tile are suspended directly from cast-iron hangers, which provide a positive spacing for expansion and form a completely bolted construction of great simplicity and strength. A considerable flexibility of tile arrangement is possible, as shown in the drawing. For roofs operated

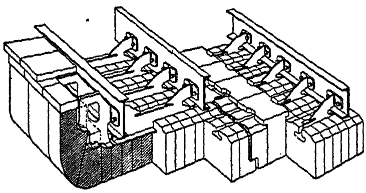


Figure 174. Suspended arch, showing both the horizontal arch and nose construction.

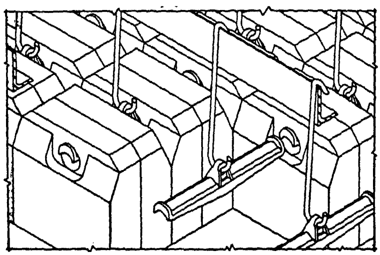


Figure 175. Arch in which four tile are assembled on a cast-iron bar which is connected by a hook to supporting

under pressure and provided with insulation, a modified design can be used (not shown in the illustration) where fixed centering is maintained.

In still another design of suspended arch the tile are supported from steel tubes by means of individual castings, with the tubes fastened to the supporting structure by eye bolts. The arch can be insulated over a large area, and the design is very flexible.

An arch which is assembled in units of four tile is shown in Figure 175, where the four tile are assembled on a cast-iron bar connected by a hook to

supporting angles. The tile can be replaced from above or from below, and a large area of the arch can be insulated. A typical nose construction is made up of radial tile supported in a manner similar to that of the flat arch.

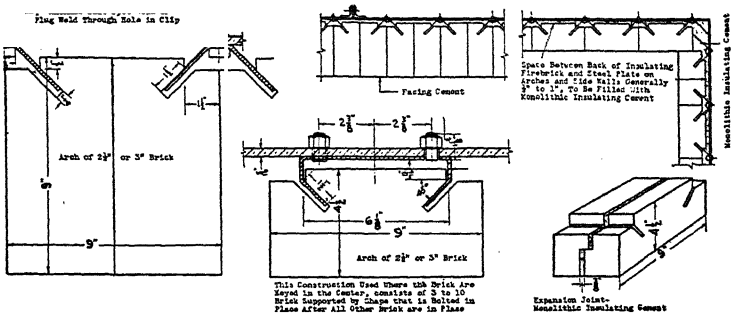



Figure 176. Method of constructing flat arch and side walls of insulating brick supported by steel plates.

Insulating refractories may also be applied to suspended arches. Figure 176 shows a method of support by bent steel plates, and Figure 177 shows a method using pipes through holes in the bricks. This kind of refractory

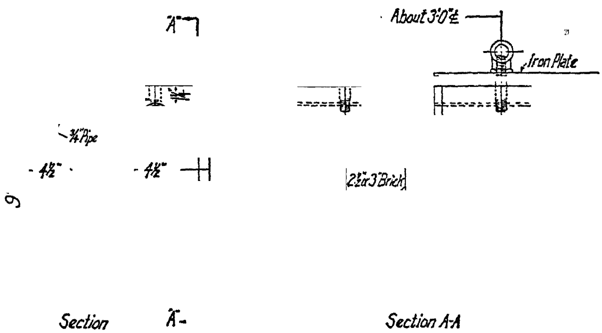
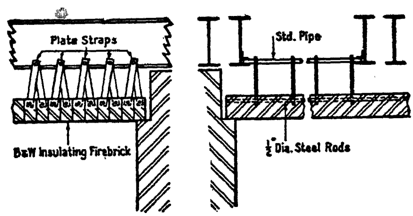



Figure 177. Method of constructing flat arch supported by iron pipe which extend through holes in insulating refractory brick.

is soft and easily cut, so that the slots and holes required may be readily formed in the arch tile.

Other methods for supporting insulating refractories are illustrated in Figure 178, where the bricks are strung on rods and supported by steel

Figure 178. Flat arch constructed of insulating firebrick strung on rods and supported by steel straps to pipe supports above.



straps to pipe supports, and where the bricks with a T-slot are fastened to I-beams above by means of steel clips, as in Figure 179.

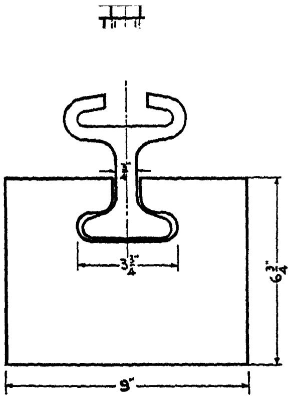



Figure 179. Furnace arch is constructed of bricks with a T-slot, which, by means of steel clips, are fastened to I-beams, as shown above.

**Suspended Walls.** Although the suspended type of arch has been applied to all kinds of industrial heating furnaces, including the moving covers for soaking pits, the suspended wall has been confined almost entirely to boiler furnaces. The principles used in this type of wall have possibilities in heating furnaces, and a review of the available designs is not out of place in this discussion.

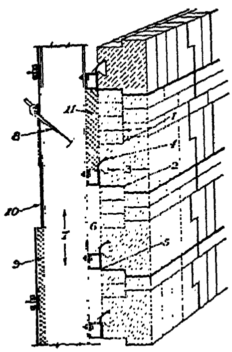


Figure 180. Supported refractory wall in which special tile are locked in place by castings.

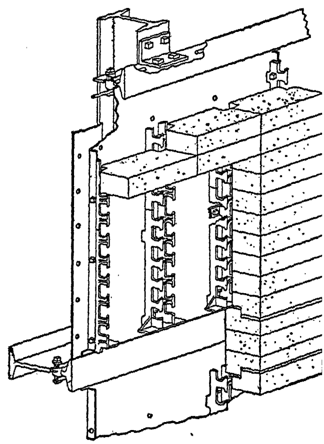


Figure 181. Supporting method for a wall of light weight refractories.

Figure 180 shows a method of supporting a refractory wall where the special tile are locked in place by castings and intermediate tile are arranged with broken joints to seal the wall. These intermediate tile are held in place by air-setting high-temperature cement. Metal parts are reduced to a

minimum, and insulation may be applied as shown. A somewhat similar supporting method for a wall of light weight refractories is shown in Figure 181. By either method, cumulative loading of the hot refractories is avoided by transferring the load to the supporting framework at frequent intervals in the height.

Figure 182 is a section of another wall-supporting method, where the blocks are supported on a series of cast-iron shelves to avoid cumulative loading and are provided with loose-fitting anchors to permit expansion.

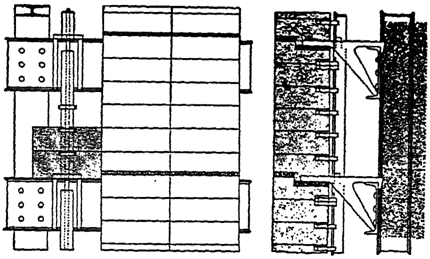


Figure 182. Wall in which blocks are supported on a series of cast-iron shelves to avoid cumulative loading.

Still another method of construction is illustrated by Figure 183, in which the cast-iron horizontal supports are fastened to the vertical columns. Vertical cast-iron supports are hung from the horizontal castings and support the tile in separate sections. All joints are broken, and the faces of the tile are corrugated to prevent pieces from falling out of the wall as the result of spalling.

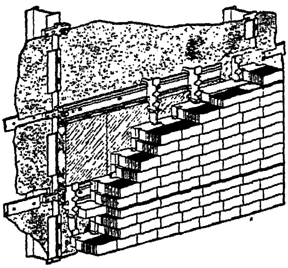


Figure 183. Insulated wall in which cast-iron horizontal supports are fastened to vertical columns.

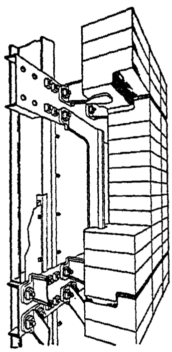


Figure 184. Supported wall in which tile fit on cast-iron hangers bolted to the supporting panel work.

Another design of air-cooled supported wall is shown in Figure 184, where the tile fit on cast-iron hangers bolted to the supporting structure. The wall is arranged in vertical sections individually supported by special castings, and the joints between the sections are packed with plastic refractory to protect the supporting castings.

An integral-panel wall construction is shown in Figure 185. Insulating firebricks are strung on rods extending the height of, and attached to, the separate panels of each casing. Each panel assembly may be constructed

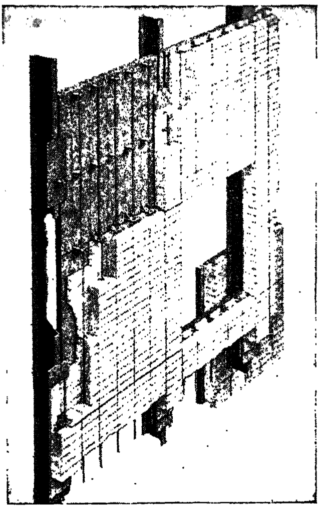


Figure 185. Integral-panel wall construction in which insulating firebrick are strung on rods attached to separate panels of casing.

individually and the units then fastened together. This feature allows any of the panels to be removed for purposes of inspection, cleaning, or maintenance.

A simple method for supporting a wall of either firebrick or light refractory bricks is shown in Figure 186. This wall is supported in sections by plate and angle supports of flexible design.

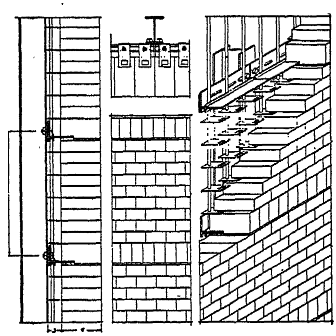


Figure 186. Wall of standard firebrick or insulating refractory brick supported in sections by plate and angle supports.

Figure 187 shows a well-known type of suspended wall design, modified for conditions which are too severe for fireclay refractories. In this design, silicon carbide facing blocks are locked to fireclay supporting blocks carried on brackets. Replacement can be made quickly, and cumulative loading is

avoided by the design. Joints between the facing blocks and supporting blocks are staggered to reduce leakage through the wall.

**Other Forms of Suspension.** An application of anchored plastic material is shown in Figure 188, in which a rammed plastic facing is anchored to a brick wall by means of refractory anchors. The plastic facing is cut into sections about three feet square to allow for expansion. The flexibility of this form of construction is great.

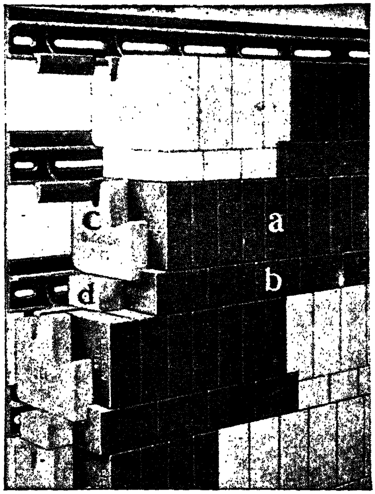



Figure 187. Suspended wall design in which silicon carbide facing blocks are locked to fireclay supporting blocks carried on brackets.

A flat arch for doors or narrow furnaces is shown in Figure 189. In this design, no supporting members are required and the flat arch is accomplished by special shapes interlocked in such a manner as to be self-supporting. These arches are made for spans up to about 8 feet, and are very useful in many industrial furnace applications where plain tile tend to crack under bending stress when spanning flues, doors, and narrow chambers.

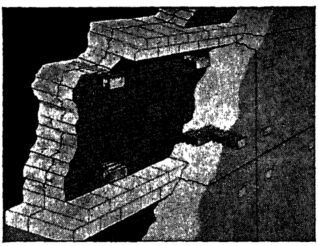


Figure 188. Supported wall construction in which rammed plastic facing is anchored to brick wall by means of refractory anchors.

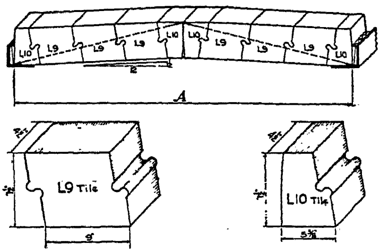



Figure 189. Flat arch for doors or narrow furnaces utilizing special interlocking shapes which are self-supported.

Table 36. Properties of Common Refractories

| Refractory | Principal components (%) | | Melting point (deg F) | Specific gravity | Mean specific heat (70–1830 deg F) | Thermal expansion (in/ft) at 1200 deg F | Thermal expansion (in/ft) at 2000 deg F | Thermal conductivity (Btu/hr/sq ft/deg F/ft thickness) | |
|---|---|---|---|---|---|---|---|---|---|
| Firebrick | $SiO_2$<br>$Al_2O_3$ | 54<br>41 | 3260 | 2.00 | 0.26 | 0.03 | 0.06 | 0.67<br>.83 | (70 to 1830 deg F)<br>(at 2000 deg F) |
| Silica brick | $SiO_2$<br>$CaO$ | 96<br>2 | | 1.84 | .26 | .14 | .15 | .70 | (70 to 1830 deg F) |
| Mullite | $Al_2O_3$<br>$SiO_2$ | 72<br>28 | 3290 | 3.03 | .18 | .05 | .10 | | |
| Sillimanite | $Al_2O_3$<br>$SiO_2$ | 63<br>37 | 3290 | 3.24 | .18 | | | | |
| Magnesite | $MgO$<br>$SiO_2$<br>$CaO$ | 85<br>4<br>3 | | 2.61 | .28 | .08 | .17 | 2.33 | (at 2000 deg F) |
| Chromite | $Cr_2O_3$<br>$FeO$ | 68<br>32 | 3956 | 4.5 | .22 | .08 | .24 | 1.38 | (70 to 1830 deg F) |
| Silicon carbide | Si<br>C | 70<br>30 | 4082 | 3.2 | .18 | | .06 | 5.0 to 6.0<br>9.0 | (70 to 1830 deg F)<br>(at 1600 deg F) |
| Dolomite | $CaO$<br>$MgO$<br>$Co_2$ | 30<br>22<br>48 | | 2.9 | .22 | | .17 | | |
| Magnesia spinel | $MgO$<br>$Al_2O_3$ | 28<br>72 | 3875 | 3.6 | .26 | | .10 | 1.10 | (at 1600 deg F) |
| Graphite<br>Silocel brick | C | 100 | 5432 | 2.3<br>0.4 | .29<br>.25 | | .03 | <br>0.09 | <br>(at 1200 deg F) |
| Insulating firebrick (2300) | | | | 0.7 | .25 | .05 | .09 | .21<br>.40 | (at 1200 deg F)<br>(at 2000 deg F) |

In conclusion Tables 36 and 37 on the physical properties of common heat-resisting alloys and refractories are included for reference.

Table 37. Properties of Heat-resisting Alloys

| Common name | Analysis (%) Chrome | Analysis (%) Nickel | Thermal conductivity (Btu/hr/sq ft/deg F/ft thickness) | Specific gravity | Melting point (deg F) | Specific heat at room temp. | Mean coefficient expansion (32–212 deg F $\times 10^{-5}$) |
|---|---|---|---|---|---|---|---|
| Monel metal | | 60–70 | 14.5 | 8.80 | 2415 | 0.127 | 0.80 |
| Stainless 18–8 | 8 | 18 | 12.5 | 7.86 | 2550 | .118 | .89 |
| 17 Chrome | 15–18 | — | 15.3 | 7.70 | 2714 | .110 | .58 |
| "25–12" | 24–26 | 11–13 | 9.4 | 7.00 | 2620 | .134 | .91 |
| "35–15" | 15 | 35 | 5.8 | 7.92 | 2645 | .112 | .75 |
| "65–15" | 19–21 | 66–68 | 6.2 | 8.05 | 2625 | .114 | .70 |
| "80–20" | 20 | 80 | 8.7 | 8.36 | 2550 | .104 | .73 |

# Chapter 7

## Steel Mill Furnaces

The purpose of this chapter on furnaces for steel mills is to study the developments in the varied furnace equipment used in the different heating processes. These are divided according to the form of the finished product, as follows:

(1) Furnaces for bars.
(2) Furnaces for rods and wire.
(3) Furnaces for pipes and tubes.
(4) Furnaces for sheets and strip.

In each of these classifications numerous heat applications are involved, where in many cases the furnaces are in a stage of transition from traditional designs to more modern arrangements. A study of these changes and the reasons for them is of interest to both operators and engineers.

### Furnaces for Bars

As an aid in obtaining a broad picture of the furnace requirements in the manufacture of bars, the diagram of Figure 190 has been prepared. In this diagram the flow of steel from the ingot to the finished product through the various mills in common use is shown. The purpose of the diagram is to indicate the points of heat application rather than to bring out in detail any other steps in the manufacture, and for that reason many of the steps are covered by very general notations. The heating equipment involved is boxed in solid lines where generally used and in dotted lines where application is only occasional.

The soaking pits for the heating of ingots from the open-hearth or electric melting furnaces are the first heating equipment in the process and are also the one heating equipment which is common to all classes of steel products. After passing through the blooming mill or slabbing mill in conjunction with these pits, the product separates to the various successive processes, but all cast ingots for the first mill (or hammer or press) are first soaked in the pits. These pits were originally refractory holes without means for heating and were intended to insulate the ingots with a minimum of heat loss by radiation while the molten interior solidified and diffused its heat uniformly to the rest of the ingot. With increased production and metallurgical complications from the variety of different steels, the need for heat

in these pits was soon developed, and the Siemens regenerative furnace arrangement was universally adopted for the purpose very early in the history of steel manufacture. Subsequent improvements in all other classes of heating were not applied to this equipment until recently, when the idea

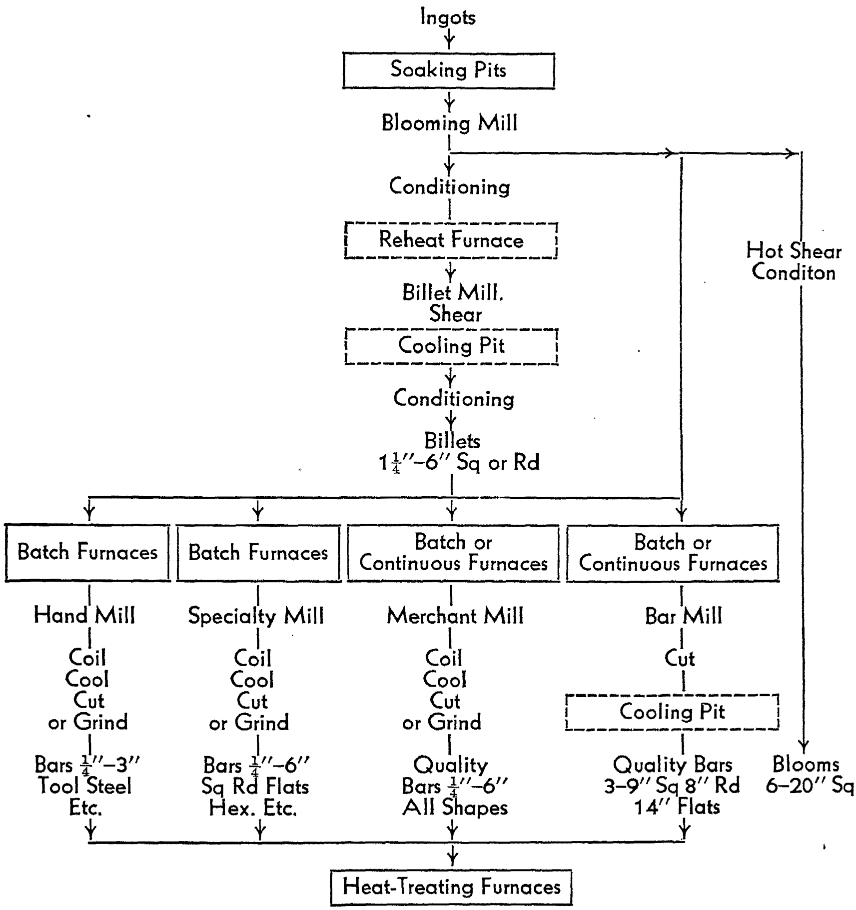



Figure 190.

developed that controlled heating in the initial stage was as important as metallurgically correct heating in the later steps in the manufacture.

Immediately, the regenerative furnace was widely condemned and replaced by furnaces of a recuperative type equipped in all cases with the best available combustion and temperature control. Calm analysis now indicates that this control equipment has been to a larger extent responsible for the improved operation than has the change in the furnace type or

design. A regenerative furnace with forced draft and combustion control will operate with all of the good results of the more novel designs.

A tabulation of these good results and the reasons for them is as follows:

| Effect | Cause |
|---|---|
| Reduced scale and decarburization. | Pressure control and sealed covers to exclude free air. Also, temperature control and control of fuel-air ratio |
| Improved bottom-making and less maintenance. | Automatic temperature limitation. |
| More uniform heating. | Automatic control of temperature and furnace pressure. Automatic reversals of regenerative pits. |
| Reduced "washing." | Exclusion of air by furnace pressure and, of lesser importance, ratio and temperature control. |
| Fuel economy. | Sealed covers, pressure and ratio control. |

The principal types of pits which by their utilization of modern burners and controls are responsible for the developments in this field are illustrated in the accompanying illustration.

Figure 191 shows the cross-section of a one-way fired pit in which the burner fires through one end wall above the ingots and the flue gases leave the pit through ports in the same wall at the bottom. One recuperator is used for a battery of holes or pits, and all forms of automatic control are employed.

Figure 192 is a pit of circular cross-section in which a number of small premixing burners are fired tangentially near the bottom. The waste gases leave the pit through a port in the center of the bottom, and means for recuperation can be used in conjunction with these pits. Automatic temperature, pressure, and ratio control are used.

In the design of Figure 193, the section of the pit is square and all fuel is burned through an opening in the center of the bottom. The waste gases leave through wall ports connecting directly with the recuperators on each side of the pit. A feature of this pit is the high preheat temperature and resulting low fuel consumption. Sealed covers and all forms of automatic control are features of the design.

As has been stated, the real novelty of all the new pits is the application of control devices. Equipped with similar control and provided with combustion air under pressure, the regenerative pit blocks are equally modern, and the choice between them and the one-way fired designs is not easy. Quality of heating is equally good and the question of floor space arrangement is probably the most important consideration. It is probable that future installations will be of both the regenerative and recuperative designs. Figure 194 shows a regenerative pit.

The next step is the rolling of billets, and if this process is at all continuous, the continuous type of furnace is preferred because of the fuel

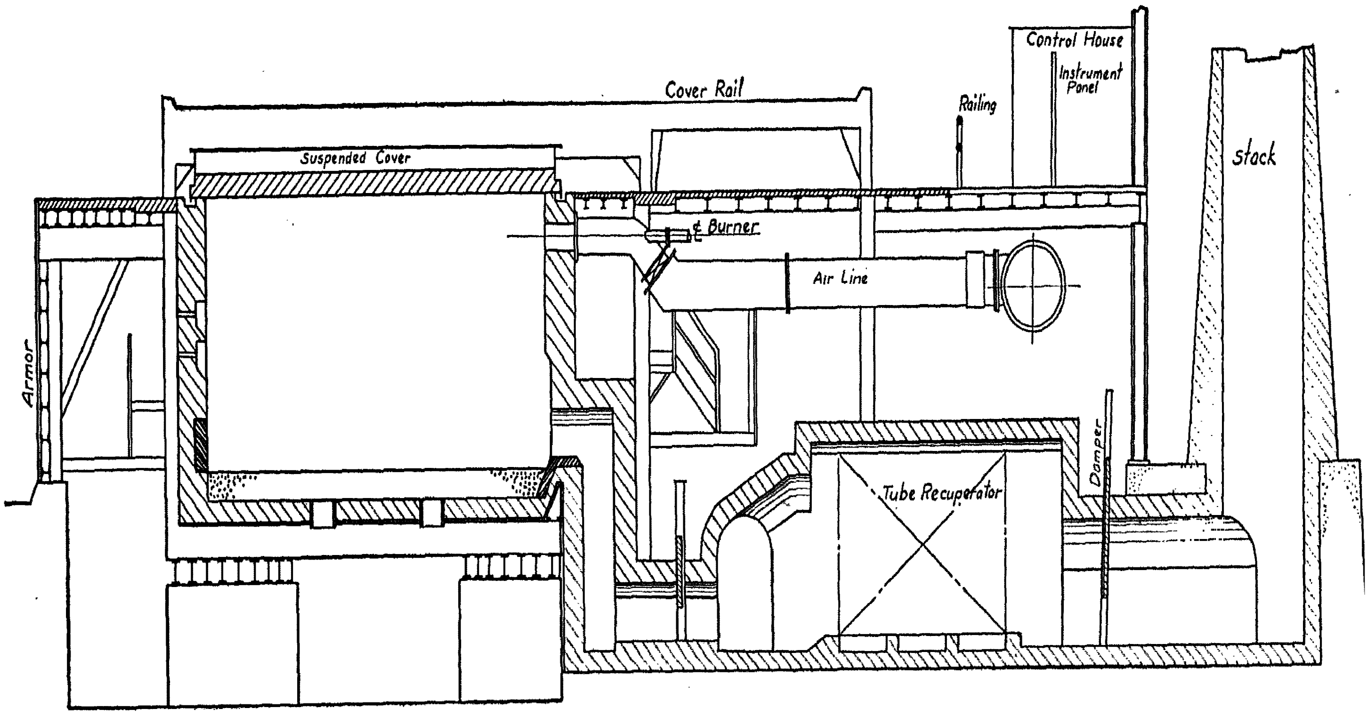



Figure 191. One-way fired soaking pit.

economy which can be realized from the counter flow of products of combustion and steel to be heated. The principal disadvantages from the use of large continuous furnaces for the heating are the lack of flexibility in production and the excessive time for which the steel is exposed to the furnace atmosphere, particularly in the event of slow rolling or mill delays.

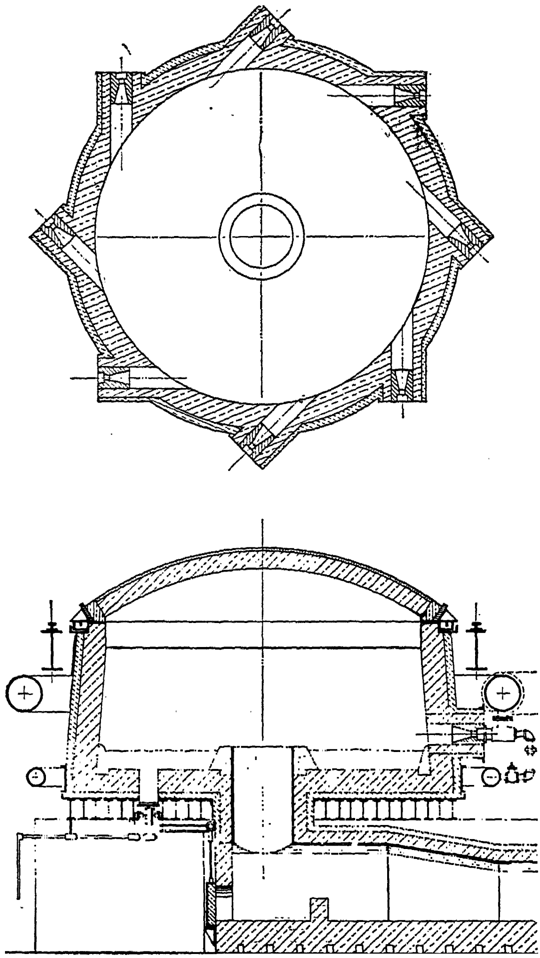


Figure 192. Circular soaking pit.

The importance of the first objection depends entirely upon the contemplated rolling schedule, and the alternate plan for batch furnaces in parallel arrangement with special handling devices is discussed further on. The second objection is a metallurgical one and is of increasing importance with the greater necessity for the control of surface and decarburization.

Almost all continuous furnaces for billets are of the simple pusher type, fired from the discharge end, which may be arranged for either gravity discharge of the billets through the end or pusher discharge through a side

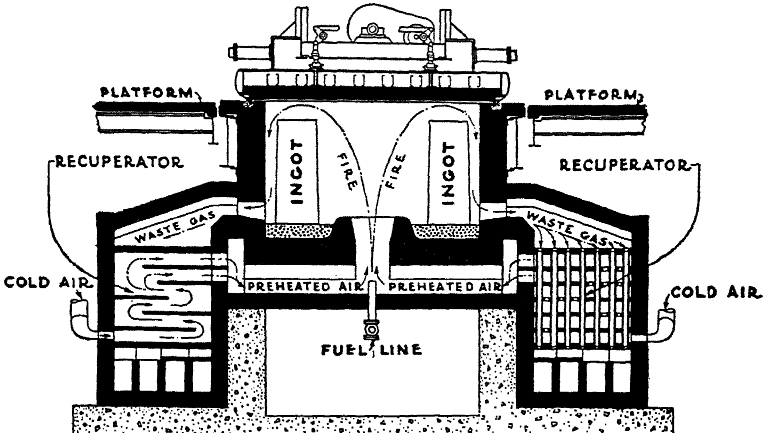



Figure 193. Bottom fired soaking pit.

door. The side discharge is much to be preferred where the control of atmosphere is important. Most of the older furnaces were built with either regenerative or recuperative heat-saving devices of surprising complication in view of the relatively small amount of heat left in the waste gases from

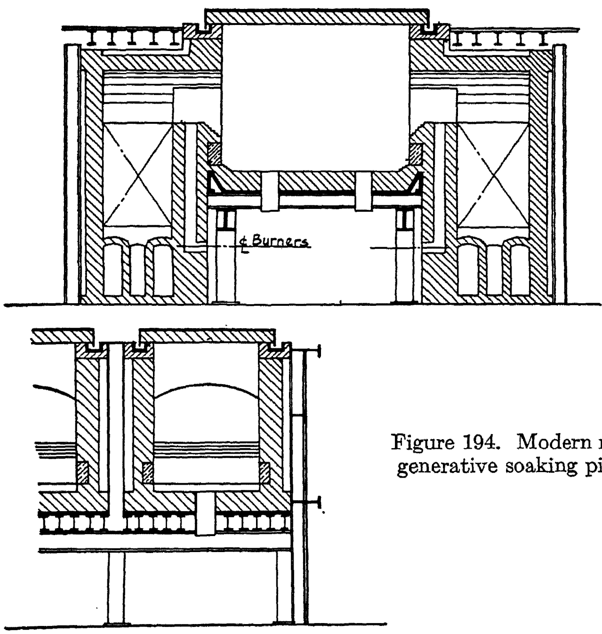



Figure 194. Modern regenerative soaking pit.

this type of furnace. The heat-saving devices are usually found to have been abandoned years before, as have the stack dampers, with the result that excessive draft is characteristic of these old and still common furnaces.

The flame passes over the steel where small billets are heated, and is split for top and bottom heating of larger billets, or blooms, by elevating the conveying rails on longitudinal piers through the furnace. The generally accepted point of division between the two types is a 4-inch thickness of billet or slab.

A list of improvements in this type of furnace in recent years should include:

(1) Triple-firing, by which the heating can be better regulated to the production rate. The steel is heated by flame above and below to the point where at maximum production rate, the surface has reached temperature. In the remainder of the furnace it is heated from above only for soaking. In this section excessive furnace temperatures are avoided at the higher rates of production because it has been possible to heat rapidly in the initial stages. Figure 195 shows furnaces of this type.

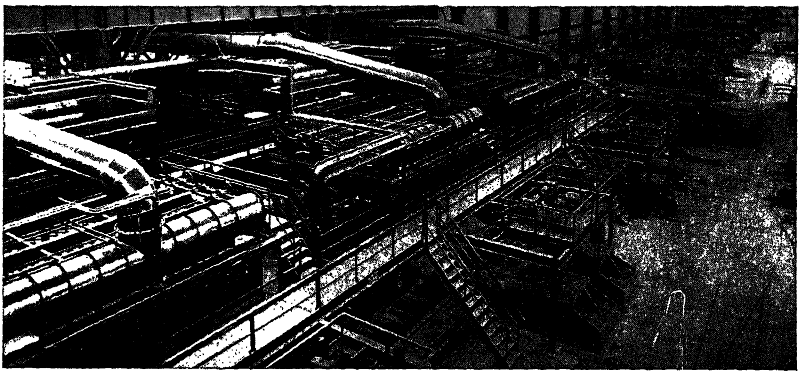


Figure 195. Three triple-fired continuous billet-heating furnaces.

(2) Quality at reduced cost has been obtained by application of crude fuels to the heating section and of refined fuels to the soaking zone.
(3) Methods of by-passing the flame to control decarburization.
(4) Application of control of temperature, fuel-air ratio, and furnace pressure.
(5) Metallic recuperators for conserving heat at small initial cost and floor space requirement.
(6) Developments in suspended flat arches have been important in the design of continuous furnaces, especially those exceeding about 10 ft in width. The original Morgan furnace with longitudinal arches on

water-cooled suspended pipes was designed to get away from the bad effects of the high crown of a sprung-arch furnace of any width. Suspended flat arches of modern design permit the application of scientific roof lines and resulting improvement in heat transfer, uniformity of temperature, and fuel economy.

(7) The adoption of separate preheating and finishing furnaces, for the control of surface of stainless steels and for the control of decarburization of alloy and high-carbon grades. The preheat furnace with maximum temperature of about 1800 deg F can be fully mechanical, and the finishing furnace at very high temperature can be either continuous or batch type.

Future developments will no doubt include more refined control of raw fuels in order to realize the advantages in cost without sacrifice in quality of heating.

The heating rates in continuous furnaces for billets vary from 20 to 80 lbs per sq ft of hearth per hour, with best results prevailing at about 40 to

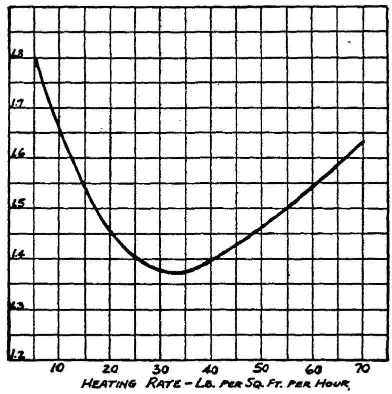



Figure 196. Effect of heating rate on economy of continuous billet furnaces.

50 lbs per sq ft per hour, where heating quality and fuel economy are well balanced. Figure 196 gives the approximate relation between economy and rate of heating in this type of furnace. The economy of a continuous furnace for billets, expressed in millions of Btu per net ton (2000 lbs) of steel heated is between 1,400,000 Btu for modern furnaces with good control and 3,500,000 Btu for old furnaces with no control and with excessive stack draft. These figures are for average production rates.

As has been stated, the alternative to continuous furnaces is the use of batch furnaces, the choice being largely dependent upon the size and variety of orders to be rolled. For alloy steels or other products rolled in small amounts at different finishing temperatures, or for pieces which cannot be satisfactorily pushed continuously, the batch furnace is a good solution.

In passing, the rotary-hearth furnace should be mentioned in connection with the heating of billets, as in Figure 197. This type of furnace has been successfully used for the high-temperature heating of forgings, and to some extent in billet heating. Such a furnace is of the batch type in that the

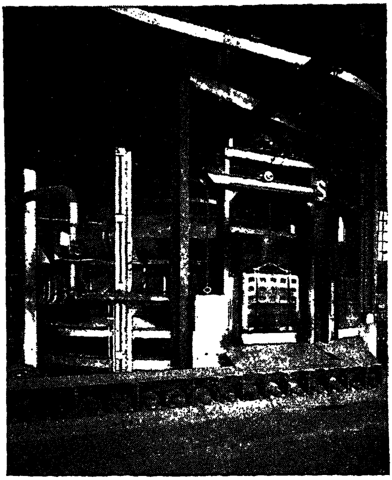


Figure 197. Rotary-hearth billet-heating furnace capable of handling square or round billets 5 ft long.

product is charged and discharged at about the same point, but is continuous in that the pieces are carried through the furnace on a rotating bottom.

The usual batch furnace for billets is a rectangular chamber with front doors and end firing, as shown in Figure 198. If heat-saving devices are employed, they may be either regenerators at both ends with reversing

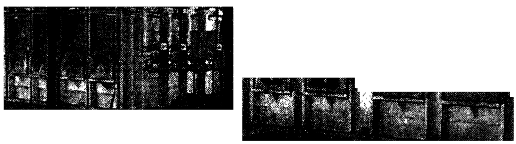


Figure 198. Batch-type billet-heating furnaces.

operation as found in older furnaces, or metal or silicon carbide recuperators, as used in more modern furnaces.

By arranging these furnaces in line and mobilizing a mechanical charging machine to operate rapidly along the front of the furnaces, all the advantages of continuous operation except fuel economy may be realized. Addi-

tional benefits of simplicity, low maintenance, and flexibility are inherent in this arrangement. Since the number of such units in operation may be adjusted to production, and since each unit may be operated at a different temperature, the advantage of flexibility is an important consideration.

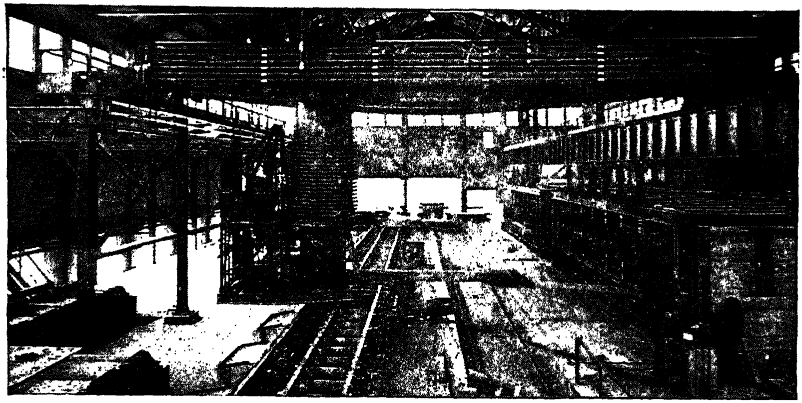


Figure 199. Crane charging machine for batch-type billet-heating furnaces.

The arrangement is not new, having been used in many early installations, but it was forgotten in the years of rapidly increasing production and is only now being recognized as a solution for recent production conditions in many alloy steel mills. The handling equipment may be on fixed tracks or on a crane, as in Figure 199, or may operate from a swivel collector cable as in Figure 200.

Figure 200. Charging machine collector type without rails, for batch-type billet-heating furnaces.

The maximum length of these furnaces for uniform heating with end firing, whether with hot or cold air, is about 30 feet, and the depth is limited only by structural considerations. The maximum depth commonly required is about 15 feet.

The older regenerative furnaces are usually found to operate with a high draft, which is characteristic of the original Siemens principle. By the use of forced air from a fan and by automatic regulation of the stack damper to maintain pressure in the furnace, this condition may be corrected and the quality of heating greatly improved. Furnaces of recent design are fired from both ends simultaneously by burners, even in the case of raw producer gas. With refined gases such as natural gas or coke-oven gas, burners of the luminous or long-flame type are most commonly selected for this application.

An innovation in the firing of such furnaces is the use of silicon carbide chambers at the ends of the furnace, in which the fuel is burned. After complete combustion in these chambers, the resulting gases leave the chamber and pass over the heating material. The advantages of this design include a better atmosphere for the heating of alloy billets of all kinds and simplified firing, since only one burner is required at each end of the furnace. This latter advantage is especially important in the case of fuel oil. The design is intended for alloy billets rolled at temperatures under 2000 deg F where scale and decarburization are especially important.

For all alloys and tool steels the use of some form of baffle or combustion chamber has been found to be beneficial to good heating, because the reactions of combustion can be completed before the gases come in contact with the steel. Control of the effect on steel also requires a positive furnace pressure to exclude free air, which is an active decarburizer. Since scaling and decarburization both increase rapidly with temperature in the range required for billet rolling, the control of temperature to prevent any overheating will show benefits in the metallurgical results as well as in the mechanical advantages of rolling a uniformly heated steel. The control of fuel-air ratio is the least important of the controls which have been mentioned, but does definitely affect the results obtained (see Chapter 1).

The principal consideration in the construction of these furnaces is extreme ruggedness, to withstand the effect of the high temperatures and hard usage involved in handling heavy billets. Provision must be made for the easy replacement of sills, chill plates, and buckstays. Water-cooling of arch plates and cheek plates at the doors is recommended.

The production from furnaces of this kind is from 20 to 40 lbs per sq ft of furnace hearth per hour, 25 lbs per sq ft being a good design figure. The fuel consumption without heat-saving appliances is from 4.5 to 6.0 million Btu fired per net ton heated for rolling temperatures above 2000 deg F and about 3.5 to 5.0 million Btu per net ton for steel rolled at temperatures below 2000 deg F. Regenerative and recuperative furnaces will require about 20 per cent less than the above figures. The furnaces cool during charging and must necessarily be cooled further before charging high carbon or alloy steels, which accounts for the low average heating rates and higher fuel consumptions than are obtained with continuous furnaces.

Before the widespread use of alloy steels, the heat-treating of bars by the steel mills did not involve anything elaborate in furnace equipment. With the growth of metallurgy and the production of many different heat-treated steels, the heat treating increased in volume and in the necessity for accuracy at high rates of production. The various processes developed included accurate heating for annealing, normalizing, quenching, tempering, and strain-drawing.

The principal types of furnaces adopted by the steel mills for this work include:

(1) Pit furnaces.
(2) Car-type furnaces.
(3) Hood-type furnaces.
(4) Batch-type hearth furnaces.
(5) Continuous furnaces.

*Pit furnaces* are used either for slow cooling or for annealing. In the first case the refractory-lined rectangular pit is brought up to temperature and the steel is charged directly from the mill. The pit and steel then cool slowly without heat application, the purpose of the operation being to prevent cracking of high-carbon steels in fairly large sections, and to soften low-carbon steels for cold shearing.

In the case of pit annealing, bars weighing up to 50 tons in many cases (sometimes several hundred tons) are charged into the pit by special handling cranes, and rest on metal cradles for circulation of heat on all sides. The source of heat may be electricity, fuel oil, or gas fired from numerous small burners along the sides. The temperature range is usually from 1100 to 1700 deg F, and the total time in the furnace from 48 to 96 hours, including heating, soaking, and slow cooling. The purpose of the treatment is usually to obtain machineability in carbon steels as well as in alloy steels, and the pit furnace is used where large quantities of the same grade of steel are to be annealed. For small quantities, car-type furnaces and other types are more flexible.

*Car-type furnaces* are commonly used for annealing, as well as for quenching and tempering of bars. In the case of annealing, the charge is cooled in the furnace, and flexibility of production and temperature variation is obtained by proper selection of size and number of furnace units. For quenching, a rapid-handling crane is desirable to transfer the charge quickly from the quenching medium (see Chapter 5). For tempering, the charge is removed from the car for cooling in air. Figure 111 (p. 168) shows an installation comprising three furnaces with a gantry handling crane for bar products. With this arrangement of furnaces, quench tanks, cooling racks, and handling crane, a high degree of flexibility is possible.

Car furnaces may be heated by electricity, fuel oil, or any of the refined gases. For strain drawing (to relieve straightening or other strains in the

bars) and for tempering or other operations at low temperatures, the recirculation method of heating can be very satisfactorily applied. Figure 96 (p. 149) shows a car-type furnace of this type, and continuous furnaces may also be equipped with recirculation units mounted above the furnace.

*Hood-type furnaces* for bars are necessarily of rectangular cross-section and consist of permanent bases on which the steel is loaded and of movable furnace covers, which are moved from one base to another by means of overhead crane. These furnaces are heated by either electricity, gas, or oil. The burners may be mounted in the bases for an underfired arrangement, or in the movable furnace in the form of small, direct-fired burners or of radiant tubes. For the usual annealing operations, an installation includes two or three more bases than there are movable furnaces, in order that the charges of bars may be loaded and unloaded on the extra bases without loss of time in the operation of the heating covers. For bright-annealing installations where metal inner covers are provided to permit the use of protective gases, there may be as many as four times as many bases as there are furnaces, caused by the long cooling cycles in comparison with the time required for heating and soaking.

*Hearth furnaces* of the batch type are similar in design to car-type furnaces, except that the construction is more simple, but more labor is required for their operation. They are indicated only where small production is involved.

*Continuous furnaces* are adapted to normalizing, quenching, tempering, and strain-drawing, where slow cooling is not involved, and where relatively large tonnage at one temperature and cycle is involved. There are many forms of continuous furnaces for bars, including walking beams, pusher type with conveying shoes, and chain conveyors.

Heat-treating temperatures range from 500 to 1750 deg F, and the best type of gas burners with a high degree of mixing and automatic proportioning of fuel and air are indicated for these applications. Control of temperature is desirable in all cases to insure uniform heating and consistent metallurgical results. All modern heat-treating furnaces are insulated with at least 5 inches of insulation on the outside of firebrick walls. A rapidly increasing number of these furnaces are being constructed of light refractories for rapid heating and flexibility in changing temperatures, as well as for fuel saving. Heat-resisting alloys have made a large contribution to the design of these furnaces, and are universally used for rails, chains, conveying shoes, beams, and other parts of bar heat-treating furnaces.

## Furnaces for Rods and Wire

As was stated at the beginning of the chapter, the purpose of this discussion is to study development in heating processes and equipment involved in the manufacture of steel in its principal forms.

The present section is devoted to heating problems in the making of steel rods and wire products. Figure 201 has been prepared to illustrate graphically the points of heat application required in this phase of steel manufacture. The diagram is again general and is intended to illustrate heating

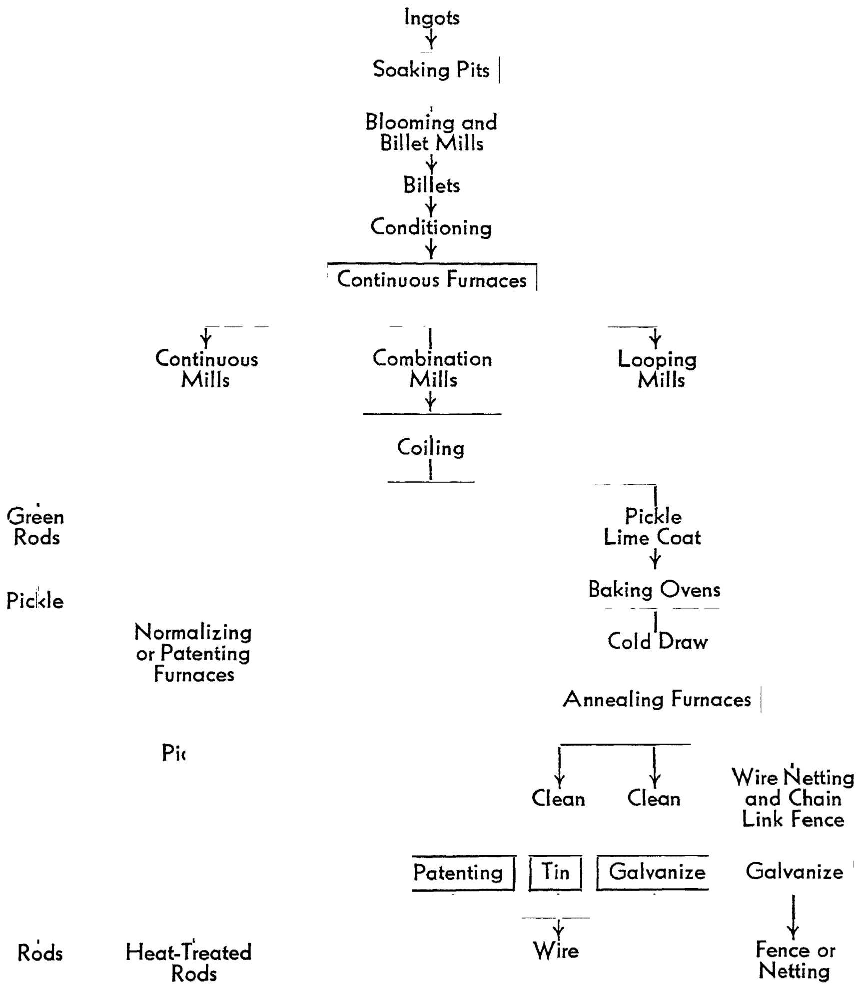



Figure 201.

requirements, rather than other details of the processes. These heating requirements have been emphasized by solid boxes in the diagram.

In Figure 201 the first application of heat is in the soaking pits, which have already been discussed in the preceding section. The next point of heat application is the billet-heating furnace, and the selection between continuous and batch furnaces is much more simple than it is in the case

of the bar products of the preceding discussion. In most cases, rods are made from relatively long billets of uniform size, and the mills can be scheduled to obtain efficient continuous operation, so that the continuous pusher type furnace is almost always indicated. Some exceptions to this condition can be found, as in the case of small hand mills for rolling small orders of varied size and analysis, in which case the paralleling of batch furnaces is desirable, for exactly the same reasons as have been given for bars in the preceding discussion.

The size of the billets to be heated depends upon the reduction desired and on other rolling considerations. On continuous mills the rods are usually rolled from small billets, averaging less than 2 inches square, while on looping mills the billets may be as large as 4 inches square. There is a tendency in the rolling of spring wire and other high-carbons and alloys to increase the billet size to approach 4 inches in order to increase the reduction on the mill, because by this method decarburization and other surface defects are reduced by distribution over a greater finished area.

As a result of the relatively small billets involved, the simple over-fired type of pusher furnace is generally employed, and little major change has taken place in the design of these furnaces. Suspended arches are usually used to achieve efficient roof lines, because all furnaces of this type must be wide to accommodate the long billets. Discharge of the billets is either through a side door or through the end, with the former arrangement preferred in all cases, because pressure control in the furnace is easily accomplished with side discharge and is very difficult with gravity discharge through the end of the furnace.

The furnace may be fired with producer gas, fuel oil, or any of the refined fuel gases. Producer gas-fired furnaces with internal ports for gas and air are still common, but with the necessity for improved quality in rod and wire products, the tendency is to adopt fuels which are capable of more accurate control. Natural gas and coke oven gas are common fuels, and are usually burned by luminous flame burners, wherein the gas and air are directed into the furnace in parallel streams and at velocities of about 20 feet per second, to obtain radiant luminosity as the result of a minimum of turbulent mixing. By applying burners about three feet apart at the end of the furnace, a uniformly applied blanket of flame may be obtained, without channeling through any part of the furnace length.

With increasing metallurgical knowledge about the effect of temperature on steels of different quality, and with increasing demand for perfection of surface of rod and wire, the necessity for control has also increased in recent years. This control involves automatic maintenance of uniform temperature, ratio of fuel and air as fired, and positive furnace pressure to exclude free air at all times (see Chapter 2).

The heated billets to a continuous type of rod mill are usually supplied

from one furnace with a width of about 32 feet and a length sufficient to heat the steel at maximum mill rating. For such a mill with a capacity of 25 gross tons per hour, and an average production of about 16 to 18 gross tons rolled per hour, the effective furnace length required is about 24 ft, and the rate of heating at the average production rate is about 49 lbs rolled per sq ft of furnace hearth per hour for these small billets. Under these conditions the overall economy of the furnace should be between 1.4 and 1.8 million Btu fired per net ton of steel rolled. With an average yield on the mill of 85 per cent, the actual heating rate in the furnace will be about 17.5 per cent greater than the rolled production, or 58 lbs heated per sq ft of effective hearth area per hour. Similarly, the economy figure is between 1.2 and 1.5 million Btu per net ton of steel actually heated in a modern furnace. The effective length used in these determinations is from the charging end to the centerline of the discharge door, and the actual length inside must be about 30 ft to allow a sufficient distance from the burner wall to the hot steel for the development of maximum flame temperature. Failure to provide this distance accounts for the condition where the point of maximum temperature is back of the discharge point, and where the steel actually cools before being discharged.

For rod mills of the looping type the larger billets are usually shorter, and the mill is served by several narrower furnaces of the same design as for the continuous mills, with the discharge frequently through the ends in existing installations. As has been stated, this is objectionable and side discharge should be arranged wherever possible. This is sometimes difficult with several furnaces heating billets only 10 ft long (a function of billet section and finished coil weight) but maximum effort is desirable.

The heating rates and economies in these furnaces heating larger billets should be about the same as for the continuous bar mill furnaces already discussed. The usual production from looping mills is between 25 and 40 gross tons per hour, and the number of furnaces required will be influenced by the maximum length of satisfactory push, which for the usual billet sizes involved is about 60 ft.

Newer rod mills are sometimes built to produce smaller bar sizes in straight lengths, but this does not in any way affect the heating problems involved.

Referring to the outline of Figure 201, the heat treatment of both rods and wire can best be discussed together, because of the fact that many of the same furnaces are used. We shall therefore consider the normalizing of rods, the annealing of rods and semi-finished wire, the annealing and spheroidizing of wire, and the patenting of rods and wire.

Rods are sometimes normalized for cold heading properties, involving heating of the rods to about 1650 deg F followed by controlled cooling, and three types of furnaces have been commonly used for this purpose.

One of these is a pusher type continuous furnace, in which single coils of rods are carried through the furnace on alloy trays. The first portion of the furnace is for thoroughly heating the rods to required temperature (about $1\frac{1}{2}$ hours for a 300-lb coil) and the remainder of the furnace is for controlled cooling through the critical range. The principal advantage of this type of furnace is the short heating cycle which reduces the difficulties from decarburization, while the main objection is that the furnace is a single-purpose unit which cannot be used for other annealing purposes in the wire mills where longer cycles are involved.

The other two types of furnace are the pit type and the hood type, which are equally suitable for normalizing and for other types of annealing, because they operate in a batch manner. In these furnaces the rods in loads up to about 5000 lbs are charged in an alloy retort, and the heating cycle is increased above the pusher type to about 5 hours for normalizing. The increase in time at high temperature is sufficient to cause difficulties with decarburization of the surface, and a protective atmosphere is usually provided in the retort.

The atmosphere used for protection is usually made from cracked hydrocarbon fuel gas (Chapter I), and a considerable amount of conditioning is required to maintain the decarburization to a depth of less than 0.005 inch from the surface of the steel, as is now frequently specified. After heating for five hours, the rods are either transferred to a protected cooling pit in the case of the pit furnace, or the hood is removed in the case of the hood furnace. The average production from one such furnace is about 10 net tons of steel per day.

Another heat-treating operation applied to rods and to cold-worked wire is spheroidizing, to change the structure of the steel for increased softness or ductility. This treatment involves an extended heating of about 14 hours at temperature in the range of about 1350 deg F, followed by slow cooling. The equipment used is either a pit-type furnace, such as has already been described, or a cylindrical hood-type furnace, illustrated by Figure 202. In either case the wire coils (in charges of about 3000 lbs) are contained in an alloy retort throughout the heating and cooling cycles. Rectangular hood-type furnaces containing several circular retorts are also frequently used where large amounts of the same treatment are involved.

On account of the long heating period (24 hour average cycles), decarburization is usually a serious problem, and must be controlled by the use of special gas atmosphere, such as that mentioned for the normalizing process (see also Chapter 1). If some dirt on the wire is not objectionable, raw natural gas can be used in some cases, because the temperature is not high enough to promote carburization (addition of carbon) as in the case of normalizing. The natural gas will crack and deposit soot on the wire, which is objectionable in many instances. Continuous heating in strands

or in individual coils will be developed further to overcome the difficulties with decarburization, although where scale is to be prevented it will be necessary to employ a muffle and protective gas atmosphere. The principal difficulty will be in the low production per unit of hearth area and the resulting large floor space requirements.

The annealing of rod and wire at various stages in its reduction by drawing through dies is another important heat application in wire manufacture. On small wire sizes this heating is done in liquid salt or in lead

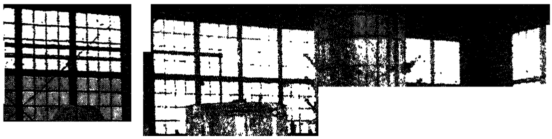


Figure 202. Circular hood furnace, radiant gas fired, for wire annealing.

pots, as will be described in more detail further on; but wire sizes above about 10 gage are usually open annealed or annealed in retorts. Open annealing produces a scaled surface and the tendency is to avoid it in anything except continuous-coil heating furnaces with short heating cycles. Coke-fired batch furnaces are still in use for open annealing with a minimum of scale and decarburization, but they are costly to operate and difficult to control. Pot annealing with iron borings and with gas atmosphere in cast-iron pots is more expensive than in modern sheet-alloy retorts with protective gas. The best furnaces for this intermediate annealing are the hood type, although pit furnaces are also used. They are usually lined with insulating refractories for rapid heating and light weight, and may be heated by electric elements, radiant tubes, or by direct-fired burners. Fans are sometimes provided for circulation of the atmosphere within the retort, although this circulation is effective only at low temperatures and with proper design is not necessary for good results.

With either the pit- or hood-type furnace the charge of wire in the retort is usually about 3000 lbs and the heating time averages about 8 to 15 hours. Part of the cooling cycle is completed before the furnace cover is removed which adds about 15 hours to the cycle. Where clean or bright finish is desired the charge remains in the sealed retort until the temperature has dropped below about 300 deg F and is protected by the special atmosphere gas in the retort during this period. Several circular retorts are often used

with a rectangular base and rectangular movable hood furnace, where production annealing of coils with protective gas atmosphere is desired.

Patenting is another heat-treating operation involved in rod and wire making. The purpose of the operation is to produce a uniform structure with some increase in tensile strength and toughness, and the method involves rapidly heating the wire or rod in strands to a temperature of about 1680 deg F, followed by cooling in air or in a lead bath at about 900 deg F.

The usual furnace for this work will accommodate up to 36 separate strands of wire on about $2\frac{1}{2}$-in centers with an average width of about 7 ft. The rod or wire ranges in size from 0.050 to 0.750 in diameter. When heating the average #5 rod (0.218-in diameter) weighing 0.11 lb per foot,

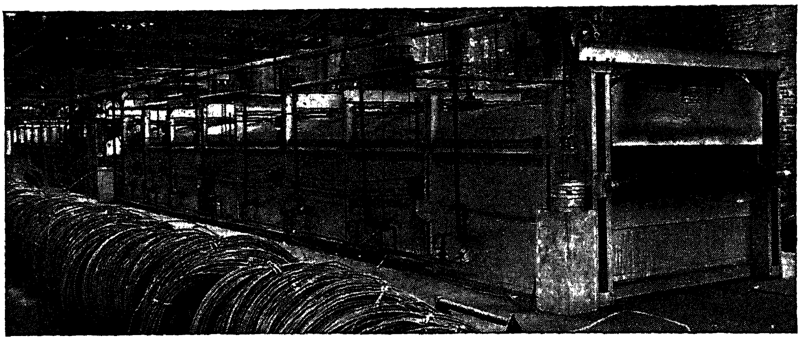


Figure 203. Rod and wire patenting furnace.

the usual speed is 20 ft per minute, although this speed can be increased by forcing the temperature of the furnace at the charging end. With a furnace 55 ft long, the heating time in the furnace is about 3 minutes and the maximum production is usually about 5500 lbs per hour, which corresponds to a heating rate of 14 lbs per sq ft of furnace hearth per hour.

The wire or rod is pulled through the furnace on the refractory bottom with provision for guiding the separate strands. This is essential because if adjacent strands are allowed to touch in their rapid passage through the furnace, cold spots and non-uniform results are produced. The furnace is heated by burners fired through the sides of the furnace above the product, and these burners are divided into several zones of automatic temperature control. The temperature of the furnace is usually several hundred degrees higher than the product, and the metal temperature is controlled by the speed of travel through the constantly regulated furnace temperature.

A similar furnace for the same work is shown in Figure 203. In this furnace the strands are supported on alloy rollers on 6-ft centers through the

length of the furnace. The rollers are driven at adjustable speed and are provided with grooves to keep the wires apart in the furnace. Firing is in combustion chambers below the rollers; this permits complete combustion of the fuel before the gases come into contact with the heated metal. At the speed at which the strands travel, and with the short heating time in the furnace, this feature is not essential for good surface conditions on either rods or wire.

Bakers are used in the wire industry to dry the lime coating which is used on the rod or wire as a lubricant in the drawing process. Rapid drying of the lime improves its lubricating properties and reduces possible embrittlement of the steel by occluded hydrogen. Until recently, these dryers, or bakers, consisted of a large brick chamber to hold rows of buggies which

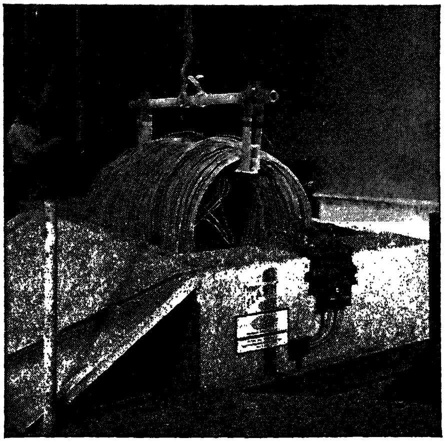


Figure 204. "Flash baker" of the recirculating type for rods.

carried piles of coils of rods or wire. The bakers were always muffled, to prevent contact of products of combustion with the lime-coated material, because the combination with products of combustion was found to pit and rust the metal, especially if these gases contained any sulfur. In the older forms of bakers the products from the combustion of the fuel passed through flues around the metal or refractory muffles, and little or no provision was made for venting the moisture driven off from the lime at the operating temperature of about 400 deg F. Baking time was about 24 hours and a large capacity had to be provided. Gradual improvement in the design of this equipment resulted from the increasing application of forced circulation and venting, with a reduction in time to about 2 hours in modern continuous bakers. These usually retain the muffled feature (indirect firing) and employ buggies or chains as the method of conveying of the coils.

A more recent development is the "flash baker" of Figure 204 in which the handling is on hooks and which will bake the lime-coated rods in as

little as 5 minutes (average 15 to 20 minutes). This arrangement will save considerable floor space and is somewhat more economical in fuel than other forms where the time in the baker is longer. These bakers are built with both direct and indirect (muffled) heating. In the indirect type the products of combustion do not come into contact with the lime, while in the direct form of heating the diluted products of combustion are circulated around the coils. In both forms, circulation at high velocity is maintained and the unusually high temperature of about 750 deg F is employed in obtaining the short baking time. Circulation is maintained by hot blast fans, and the ducts are arranged in a closed system, venting an amount of gas about equal to that taken in at the burner. The entire system is constructed of insulated sheet metal, and full automatic control of temperature is provided. No good rule can be given to cover the choice between direct and indirect bakers or between flash bakers and continuous recirculating bakers, because the requirements vary with the many different grades of wire product and because the effects of baking times and atmospheres are as yet not thoroughly understood.

Pot furnaces using salts or metals are commonly used in the wire industry. One form is the salt-bath furnace for annealing small wire and for wire which requires an unusual uniformity and surface. This salt is usually heated to a temperature of about 1300 deg F, and may be contained in a refractory-lined container heated electrically (resistance or induction) or in a cast-steel pot heated externally by gas or oil burners. The coils are suspended from hooks which are usually a part of a light monorail hoist arrangement, and several coils are charged into the pot at one time. The heating time for 900 lbs of 9-gage wire, for example, is 20 minutes. After the wire is withdrawn from the salt it is carried successively through tanks for cleaning and for reclaiming the salt. The life of externally heated pots in this service is about one year, and the cost of operation is somewhat higher than that of retort annealing with protective gas atmosphere.

Other processes involving heated pots in the wire industry include continuous-strand annealing and metallic coating (zinc, lead, and tin coating), as well as quenching and drawing treatments to produce various physical properties. Zinc coating, or galvanizing, is a very common process, and a great deal of attention has been paid to this type of coating. The principal processes developed include electrolytic deposition, combination galvanizing and annealing, flame sealing, and hot dipping with asbestos or charcoal wipe. Equipment has been developed to handle both wire in strands and fabricated fence of considerable width.

The electrolytic methods of deposition, including the Meeker, Langbein-Fanhauser, and Bethanizing processes, do not require furnace equipment and therefore need not be discussed in this book. The Galvanneal process involves an annealing furnace in conjunction with the galvanizing pot. The wire passes directly from the galvanizing kettle to the low-temperature

annealing furnace, where the heating is intended to improve the uniformity of alloying and the nature of the bond between the zinc and the iron.

The most universal method for galvanizing wire products is still the hot-dip process with asbestos or charcoal wipe. The method of wiping, whether by asbestos wipers to remove excess zinc on leaving the zinc bath (followed by air or water cooling) or by passing through a layer of charcoal on the zinc bath with a long vertical travel for cooling, does not affect the heating of the kettle.

This kettle is of steel plate, usually $1\frac{1}{4}$ in thick, and between 18 and 30 in deep for wire galvanizing, and between 15 and 25 ft long. When galvanizing wire in strands the kettle is usually between 4 and 5 ft wide. The production through a kettle 4 ft wide by 20 ft long is about 7000 lbs per hour at maximum speed, with 30 strands of $12\frac{1}{2}$-gage wire traveling at a maximum speed of 150 ft per minute. For fence the kettles may be as wide as 12 ft. The wire strands, or fabricated fence, are held in the zinc bath by means of rollers, and a complicated arrangement of take-up and pay-off spindles must be provided for operation of the unit.

The firing of these kettles requires careful attention for good results, because the formation of dross in the zinc depends to such a great extent on the temperature. For example, it is said that this dross formation, which is a dissolving action of zinc on steel, is 30 times as active at 990 deg F as it is at 910 deg F, which indicates the accuracy of temperature control required. The excessive dross in the kettle forms an insulating layer; this necessitates a higher outside kettle temperature, which further hastens the corrosive action on the kettle.

For these reasons it is essential to avoid excessive temperature at any part of the kettle, particularly at the bottom where the dross collects. To avoid excessive temperature on the outside of the kettle it is first necessary to design the kettle setting so that the transfer of heat into the bath does not exceed 10,000 Btu per sq ft of kettle area exposed to furnace heat per hour. The required heat in the bath includes both radiation from the bath surface (about 4500 Btu per hour per sq ft of bath surface), heat to the steel wire (about 112 Btu per lb of production), and heat to added zinc (about 96 lbs of zinc per ton of steel × 135 Btu per pound of zinc, or 13,000 Btu per ton of steel), and the total of these quantities must pass from the furnace through the walls of the kettle. Additional heat requirements outside the kettle include radiation from the setting and heat in the flue gases, and a typical heat balance for a galvanizing furnace for wire products will be:

| | |
|---|---|
| Heat to wire | 31.0 % of burner input |
| Bath radiation | 21.6 |
| Setting radiation | 5.6 |
| New spelter | 1.8 |
| Flue gases | 40.0 |
| | 100.0 |

A good method of firing such kettles is to provide combustion chambers under the kettle with a 3-in thickness of refractory tile between these chambers and the bottom of the kettle. For a temperature between 850 and 925 deg F in the bath, the combustion chamber temperature will be about 1300 deg F if the combustion chambers are made sufficiently large. The height of the chambers should be at least 15 in, and the firing may be accomplished by a gas or oil burner at one end, but preferably by a series of small burners along the sides. Flues are arranged in the sides of the setting near the top of the kettle. This arrangement gives excellent results with wire galvanizing kettles, where the width exceeds the depth, in spite of the prejudice against bottom firing of galvanizing kettles. Automatic control of zinc temperature is important and should be provided in two zones, each separately controlled.

Impact firing was developed on the principle that heat application in a galvanizing bath should be at the top of the bath for minimum dross formation. It is the opinion of the writer that this is not important if the kettle is relatively shallow. Another variation in the firing of galvanizing kettles is the recirculation arrangement, where products of combustion are mixed with air to controlled mixture temperature and the mixture is rapidly circulated around the pot. This arrangement is more costly but has the advantages of low temperature differential, uniform heat application, fuel saving, increased pot life, and less dross formation. In still another method of heating, all heat is transmitted to the kettle by radiation from hot tubes, so that no gases come into contact with the kettle. The tubes are internally heated by the combustion of gas and are fired from the top to develop maximum temperature at that point.

Lead annealing pans are used in the wire industry for strand annealing and for heat-treating or tempering. Such pans are frequently arranged in line with galvanizing kettles, and two pans in series are sometimes used to afford sufficient annealing time at the high speed set by the galvanizing kettle. The temperature of the lead may be from 900 to 1400 deg F and the construction and firing of the pan is the same as has been described for the galvanizing.

Kettles and pans for galvanizing and lead annealing are usually made of firebox steel plate from 1 to $1\frac{1}{2}$ in thick, with carefully welded joints. The sides and bottom are preferably of one piece, with large-radius bends at the corners, and with the ends of separate plates welded in place. With properly designed settings the life of these kettles and pans should be at least six months under the worst conditions with high-speed operation, and at least one year under average operating conditions.

Tin pots for wire are operated at only about 550 deg F, and the general arrangement and construction is similar to that described for lead and zinc.

## Furnaces for Pipes and Tubes

As in the previous discussion, Figure 205 has been prepared to illustrate the various methods of pipe and tube manufacture in a graphical manner, and to serve as an outline of subsequent discussion of heating equipment. The points of heat application are emphasized by boxes in the diagram, in which no effort has been made to bring out the details of manufacture except where heat is applied.

Again we find the soaking pit as the first heating equipment involved. After heating in these pits, the ingots from the open hearth or electric

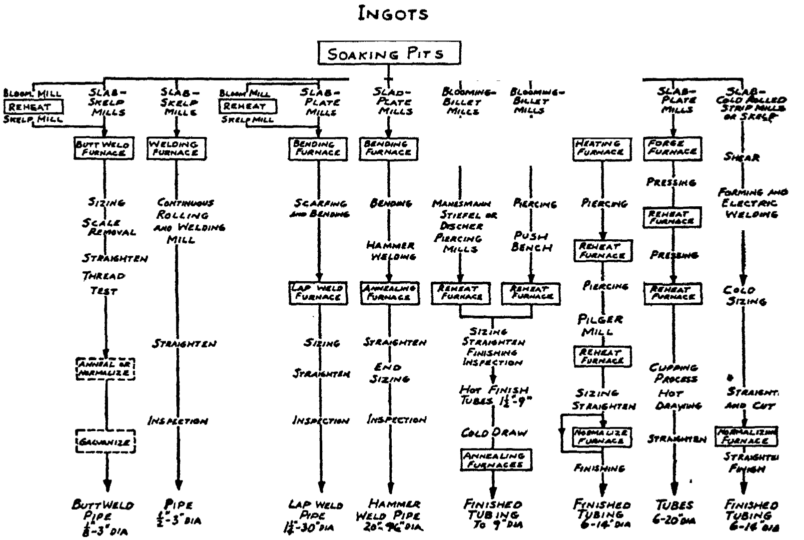



Figure 205. Chart for material flow in the manufacture of pipe and tubes.

melting furnace are rolled into blooms, billets, tube rounds, slabs, plate, or skelp for subsequent manufacture into pipe or tubes. The form of this product depends upon the subsequent method of manufacture, as does the next heating furnace involved.

Referring to Figure 205, the next form to be heated is either skelp (flat or coiled), plate, cut billets, or tube rounds. The only exceptions to this statement are the case of pilger mill tubes where the cast ingot goes directly to the mill to be heated (after proper conditioning for surface), and those cases where a reheating operation on blooms or billets is required to effect the reduction to one of the forms listed above. In the latter case, the reheating equipment for blooms or billets is a standard continuous pusher furnace or a batch furnace, already described in detail in previous discussion.

Pipe, as distinguished from tubing, may be defined as the welded product used principally for conducting water, gas, steam, or other liquids. Pipe

may be classified according to method of manufacture as butt-weld, lap-weld, or hammer-weld. All three methods are similar in principle and are determined by the size of the pipe to be made. The range of sizes for each of the three methods is shown in Figure 205.

*The butt-weld process* involves the use of pipe made from skelp — a term used to define the strip steel used for pipe making. This strip is from $\frac{1}{2}$ to 11 in wide and varies in thickness from 0.113 to 0.600 inch. The skelp, in lengths up to approximately 40 ft, is charged onto the refractory floor of a skelp furnace by means of a special handling machine. After heating to a welding temperature of about 2650 deg F the skelp is withdrawn from the

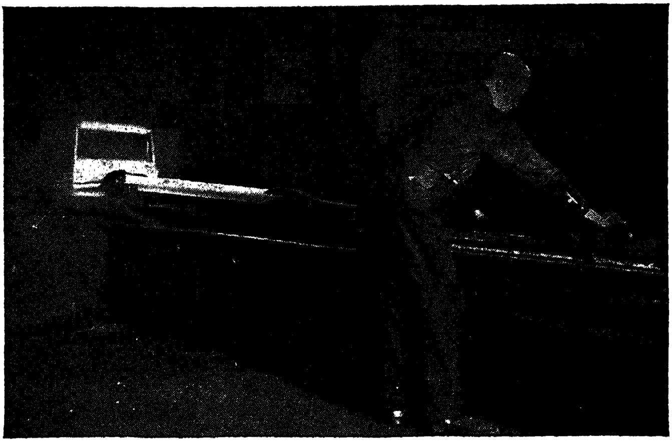


Figure 206. Butt-welding furnace, showing pipe in the process of being welded. From, "Making, Shaping and Treating of Steel.")

opposite side of the furnace as shown in Figure 206, and passes through the butt-welding machine where it is formed into pipe of the smaller sizes.

The skelp furnace is one of the few remaining furnaces in the steel mills in which the heating is yet an art, with a minimum of technical assistance provided. The furnaces are of the regenerative type to obtain the high temperatures required, and are usually constructed of silica brick. The type of scaling must be carefully controlled to accomplish welding of the pipe edges. No very definite information is available on this subject, but the loose scale resulting from the oxidizing condition characteristic of the regenerative furnace appears to be best suited to the requirements.

When the furnace is fired by producer gas, the gas and air enter through alternate internal ports along the side and leave through corresponding ports on the other side, the direction of travel being reversed at regular intervals. The construction of these furnaces is complicated by the large dimensions of the hearth in both width and length (44 × 15 ft hearths are common) and by the necessity for a continuous slot at both front and back

of the furnace, as well as by the high temperatures. These facts necessitate a very heavy binding and supporting structure.

Burners for natural gas and other fuels are fired through the sides to mix with the preheated air from the regenerators as it rises from the internal ports in the furnace. Pyrometers for indicating the furnace temperature are used to an increasing extent in this process, but automatic temperature control by regulation of the fuel has not been applied in any reported cases.

Further heating operations on the butt-weld pipe include annealing or normalizing and galvanizing, and since these operations are common to pipes and tubes made by other methods, they will be described later.

A variation in the butt-weld process is the continuous mill, using skelp in coils and operating continuously by flash-welding coil ends together without affecting the travel of the skelp. These coils weigh from 600 to 1800 lbs and are fed in single strand into a continuous furnace where the skelp is heated to about 2900 deg F for welding. The skelp is carried through the furnace on rollers and water-cooled skids and travels at a speed of 250 ft per minute for $\frac{3}{4}$-in pipe, which provides a heating time of about 0.6 minute in a furnace 150 feet in length.

The furnace is heated by gas or oil burners at close centers along its length, utilizing preheated air from metallic recuperators. Full automatic control is provided, and the atmosphere is oxidizing because of the necessity for burning the fuel at a very high rate in a furnace of small cross-section.

The rate of production from the regenerative type of skelp furnace is from 80 to 100 lbs per sq ft of hearth per hour, and the economy is about 3.8 million Btu per net ton heated for average overall conditions. Comparing with these figures the rate of heating in the continuous furnace is from 70 to 135 lbs per sq ft of hearth area per hour, and the economy is about 3.0 million Btu per net ton heated

*The lap-weld process* for larger pipes starts with plates of the size and thickness required for the finished product. The plate is first heated in a bending furnace to about 1400 deg F to prepare it for scarfing of the edges and for bending into approximately the required pipe form. This bending furnace is a simple rectangular furnace of the batch type. The size is either about 25 ft or 45 ft long, depending upon the standard pipe length to be made, while the width varies with the production required. As is the case for most of the older steel mill furnaces, the regenerative type of furnace is commonly used for this purpose. The plates, in piles or in single large pieces, are charged into the furnace at the end, either by pushing from a charging table or by a special handling machine.

After scarfing the edges and bending to approximate shape, the product is charged into the lap-weld furnace. This furnace must operate at about 2650 deg F for welding the scarfed edges of the skelp. To reduce contamination resulting from reaction between scale and furnace refractories to

form slag at these temperatures, the bottom of the furnace is constructed with gutters for draining liquid slag from the furnace.

*The hammer-weld process* for making pipe is confined to the largest sizes. The plate, of required dimensions, is in some cases heated to about 1400 deg F for initial bending to shape before hammer-welding of the seam. For many sizes of pipe made by this method, the plate is bent cold. Where required, the bending furnace used is similar to that already described for the lap-welding process. The actual welding consists in heating a section of length at a time by special portable burners and hammering the seam, so that no actual furnace equipment is required.

No exact definition prevails for tubes, although the term usually applies to the seamless product, with such exceptions as welded boiler tubes and the like. The principal classification of mills for tube-making are piercing mills (Manesmann, Discher, Pilger, Stieffel, and push-bench types) and the cupping process for large tubes. For the various processes of piercing and rolling tubes, the furnaces involved are those for heating the rounds, blooms, or ingots to be pierced, and the reheating furnaces for adding heat for further processing at some point in the forming of the finished tube.

For tubes made by the Manesmann and similar processes, the original rounds to be heated vary from 3 to 8 inches in diameter and are of different lengths. Almost all the furnaces for this purpose are long, continuous furnaces with a sloping refractory bottom on which the rounds roll from the charging end to the discharge end. The furnace is fired from the end by oil or gas burners, and side burners are usually provided from one-third to one-half the distance from the discharge end. Such burners are usually required on these furnaces because of the unusual length of the furnace and because of the wide variation in production with different sizes of rounds. The side burners increase the heating rate in the furnace for high production, but at the expense of fuel economy because the flue gases leave the furnace at higher temperatures. Where side burners are provided, care should be taken to avoid their use at average rates of production. As in the case of bars, two separate furnaces for preheating and finishing are applied for recent mills.

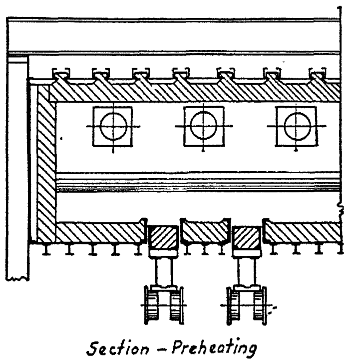
As an example of the range in mill production, a typical Manesmann mill will produce a maximum of 13 net tons per hour of 5-in diameter tubes made from 5-in diameter rounds, while the average rate is 10 net tons per hour. The furnace for this mill is 10 ft wide by 70 ft effective hearth length to the discharge door, or a total of 700 sq ft of effective hearth. At maximum production the rate of heating is about 40 lbs per sq ft of hearth per hour, while at average rate of production the heating rate is 30 lbs per sq ft per hour.

As in the case of continuous billet furnaces previously discussed, the side discharge is preferred because atmosphere conditions may be regulated

in the furnace with a small side door, whereas such regulation is difficult with end discharge. Working doors are provided along the sides of the furnace in order that the operators may control the movement of the rounds down the sloping hearth, which in most cases has a slope of $\frac{3}{4}$ in per foot of length. Longflame burners of the delayed mixing or diffusion type are well suited to this type of furnace when firing with any of the gaseous fuels.

Pilger process tubes are made from round ingots from 10 to 19 in in diameter and from 3 to 6 ft in length. These pieces are also frequently heated in roll-down furnaces with sloping refractory bottoms. These furnaces are about 10 ft wide and up to 90 ft long for a maximum production of 30 net tons per hour from two furnaces. A typical arrangement consists of two furnaces for the initial heating from cold for piercing, and one similar reheating furnace for adding the heat necessary for rolling of the hot-pierced pieces. Handling of these large, heavy pieces is extremely hot and difficult, and requires a large amount of labor.

To reduce labor costs and to improve the quality of stainless and other alloy tubes, the double furnace of Figure 207 has been developed. In the first furnace, the rounds are carried on walking beams and are preheated to



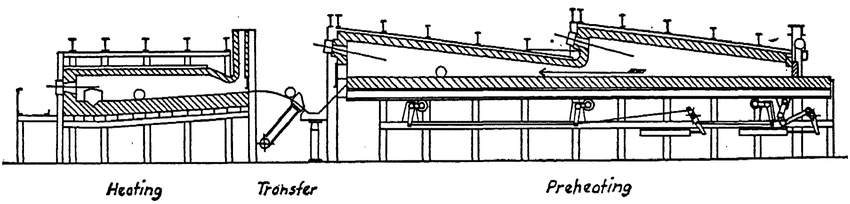




Figure 207. Double furnace for heating tube rounds.

about 1800 deg F, which is the practical limit of temperature for the walking beams. In the second furnace, the rounds are rolled down a short sloping hearth and are heated to about 2200 deg F. The transfer between furnaces is automatic and is accomplished in a very short time. Some efficiency is lost by the loss of heat in the flue gases from the second furnace,

but this is more than offset by the improved control of temperature and of time at temperature. For a maximum production of 50 net tons heated per hour, the first furnace is 60 ft long × 25 ft wide and the second furnace is 20 ft long × 25 ft wide, so that the overall maximum heating rate is 50 lb per sq ft of hearth area per hour.

Another method of heating short heavy pieces, such as those required by the Pilger or push-bench mills, utilizes a series of batch furnaces with an external handling method, such as has already been discussed in detail in the first of the preceding discussions. In one such case the mill requires the heating of pieces from 4 to 12 in square, and from 20 to 30 in long. The production is about 9 net tons per hour and 8 batch furnace chambers are provided, each with a hearth 15 ft wide by 6 ft deep. The total hearth area is 720 sq ft and the average rate of heating is 25 lbs per sq ft of hearth per hour. The fuel economy is about 3.8 million Btu per ton of steel.

The pieces to be heated are carried to the furnaces by roller conveyors and charged into the furnaces by means of tongs on a trolley. After heating they are again picked up by tongs on a monorail system and carried to the piercing press of the mill. The furnaces in this installation were fired by means of producer-gas burners at the ends of each chamber, with the products of combustion leaving the furnaces through roof ports. No stacks were used, and a temperature of 2300 deg F was easily maintained with cold combustion air. A variation of this arrangement utilizes a mechanical charging machine to charge, discharge, and convey the pieces to the mill.

After heating the original billets, the next application of heat in most tube mills is the reheating furnace. Hot, semi-finished tubes are usually rolled through the furnace on a sloping refractory bottom, and the furnaces must be wide enough to accommodate the long tubes. The length required is relatively short because the tubes are already hot and can be reheated at a rate of about 70 lbs per sq ft of hearth area per hour. For a mill production of 25 net tons per hour the usual reheating furnace will be about 50 ft wide by 12 ft long; both charging and discharging will be through side doors, because furnace atmosphere and control of scale are particularly important at this stage in the process.

The furnace is fired through either the front or rear wall and the doors for handling the tubes furnish enough flue area without additional flues. Premix burners for gaseous fuels on about 24-in centers through the width of the furnace should be used, with automatic proportioning of gas and air and automatic control of temperature which is about 1800 deg F in most cases.

After reheating, the tube passes on through the sizing and finishing mills, and after cooling is ready for further treatment, which will be described after a discussion of the final method of tube manufacture, which is the cupping process. This process for the manufacture of large seamless tubes

starts with a disc which is sheared from a steel plate and is successively pressed through circular dies to form a long cylinder. The heating processes comprise the initial heating of the steel plate or disc, and several reheating operations in the course of the successive pressing operations. All the heating and reheating is done in a typical batch-type forging furnace of simple design.

Tubes made by the electric welding process require no furnaces except for normalizing or other heat-treating processes to be described, and therefore require no further discussion.

Mention can be made at this point of one type of furnace to be found in most tube mills — the upsetting furnace for heating the ends of tubes for upsetting in a forging machine. This operation consists in increasing the thickness of the ends of the tubes for threading, so that coupling joints can be made, and is an essential operation in making tubing for the oil industry and similar products. The furnace must be designed with a continuous slot for passage of tube ends continuously through the heating chamber, and operates with a very high temperature, usually above 2400 deg F. The suspended-arch construction has solved many of the mechanical difficulties, but care must be taken with the selection of burner equipment. The reason for this care is the fact that the large radiation losses through the openings, together with the heat requirements of the steel, cause an excessive rate of combustion in the confined chamber below the steel. This condition calls for burner equipment with a good degree of premix for rapid combustion in the space available, and the use of a number of such burners firing through the rear wall of the furnace is recommended for maximum flexibility of operation. Adaptation of crude and old-fashioned burners to this requirement accounts for the complicated dog houses and other features frequently found on these furnaces.

Tubes of $2\frac{7}{8}$-in OD, with 0.217-in thick walls, can be heated in 12 minutes when rolling continuously through such a furnace; the capacity of a furnace 8 feet long inside is about 175 ends heated per hour on this size of tube. The economy is about 2.5 million Btu per net ton of steel actually exposed to the heat of the furnace. The heating rate is high because the piece is exposed to heat on all sides and because a high temperature head is maintained. The best surface conditions are obtained when the majority of the heat is applied at the discharge end of the furnace, so that the piece is gradually preheated and then suddenly exposed to very high temperature for a short time.

The principal heat-treating operations involved in pipe and tube manufacture are process annealing, finish annealing, and normalizing.

Process annealing is involved in the cold-drawing operations which are applied to many pipe and tube products for reducing to smaller size, producing sections other than round, making tubes with thin walls, or for

obtaining tubing of close accuracy and good finish. The tubes are drawn through successive dies in draw benches and after each reduction in area of about 30 per cent the tubes must be annealed to removed the strains set up by cold working. This annealing requires heating to temperatures between 900 and 1425 deg F depending upon the steel and the requirements, followed by slow cooling in the furnace. This process, together with a large part of the final annealing, is carried out in stationary-hearth batch furnaces, in car-type or hood-type furnaces, or in continuous furnaces.

The stationary-hearth furnace involves a large amount of handling labor and is usually confined to small production requirements. The under-fired car-type furnace has been developed for the annealing of tubing; Figure 166 shows a series of such furnaces in line, with a special handling crane for rapid charging and discharging of the cars. By this arrangement, the advantages of continuous operation are secured, while retaining the flexibility of production which goes with a number of heating units.

The usual car width is 6 to 7 ft, and such furnaces are built up to 60 ft long to accommodate the long tubes now manufactured. On account of the length of the cycles (3 to 8 hours in the furnace) the overall rate of heating is often less than 10 lbs per sq ft of furnace hearth per hour, with the car loaded with about 50 lbs of tubes per sq ft of area. The fuel economy varies widely on account of the variation in temperature and annealing cycles, but the average figure in most tube plants is 2.0 million Btu per net ton of tubes annealed.

The furnaces are heated by modern gas burners along both sides, and these are divided into about four zones of automatic temperature control in the longer furnaces. Air-gas ratio is automatically maintained and automatic pressure control is provided to prevent infiltration of air into the heating chamber. Cars are pulled and charged by electrically driven rack-and-pinion drives, and the refractory lining is insulated and sealed in the most modern manner. Light refractories are frequently used for lining these furnaces to save time and fuel in heating and cooling.

Hood-type furnaces may also be applied to the annealing of tubes, although the use of this type of furnace is limited at present by the length of hood which has been built, usually about 30 feet.

Continuous roller-hearth furnaces (Figure 208) are often used for tube annealing, particularly in the case of bright-annealing equipment, which is being used in an increasing number of tube mills. The tubes travel through such a furnace lengthwise on externally driven alloy rollers.

In the case of bright annealing with protective gas in the furnace, heating is accomplished by either electricity or fuel-fired radiant tubes. A long cooling chamber, water-cooled and also filled with protective gas, must be provided for bright annealing. The cooling chamber must be about twice the length of the heating chamber, which in turn is determined from the

production required, on the basis of about 25 to 30 lbs of steel heated per sq ft of heating chamber hearth area per hour.

These roller-hearth furnaces are designed to handle tubes from $\frac{1}{2}$ to 8 in in diameter, of all wall thicknesses, and in lengths usually about 25 ft. The temperature variation is between 1200 and 1700 deg F, and practically all grades of steel are heated for clean and bright annealing and normalizing, commercially free from decarburization. The heating time will vary with the diameter and wall thickness, and is from 4 minutes, for

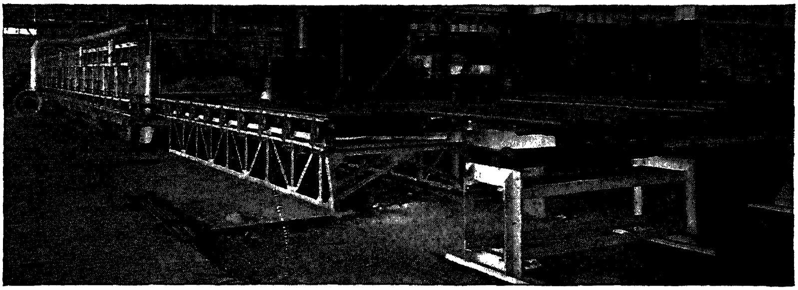


Figure 208. Tube normalizing furnace with roller hearth.

$\frac{1}{2}$-in diameter by 0.032-in wall tubes, to 35 minutes for 3-in diameter by 0.250-in wall tubes. The overall length of such equipment for a production of 2000 lbs per hour is about 160 ft.

The normalizing of certain classes of larger tubes, particularly those for the oil industry, is frequently specified to relieve strains in the steel structure. The operation consists in heating the tubes to a temperature of about 1650 deg F and discharging them into the air for fast cooling. This treatment requires the use of a continuous furnace, such as that shown in Figure 209. Such furnaces are usually about 40 ft wide by about 20 ft long for heating 10 net tons per hour at a rate of 25 lbs per sq ft of hearth per hour. Fuel economy is about 1.3 million Btu per ton of tubes normalized.

A number of different handling devices have been applied to this purpose, including chains and walking beams, but the best method for handling tubes of the size involved is to roll them down a solid sloping hearth. To avoid excessive expensive alloy, the chains have alloy fingers projecting through slots in the bottom, which prevent underfiring and allow objectionable infiltration of cold air through the bottom slots, which causes cold spots on the relatively thin tube walls. The walking-beam design is expensive and requires a shut-down in the event of the failure of any part of the mechanism.

In the sloping-hearth furnace the slope is $\frac{3}{4}$-in per foot of length, and

additional labor is not required for the handling of these large tubes. The tubes are charged through the end, which is arranged with a slot and operating door for closing the entrance. Discharge is through a small door by pushing the tube out over a heavy cast-iron groove construction in the furnace. The arch is of the suspended design in all cases, and is usually arranged with a step through which burners are fired in the center of the furnace, to form two zones of temperature control in the length of the furnace. Burners are also fired under the hearth; and with the tubes rolling in the furnace a very uniform application of heat is obtained.

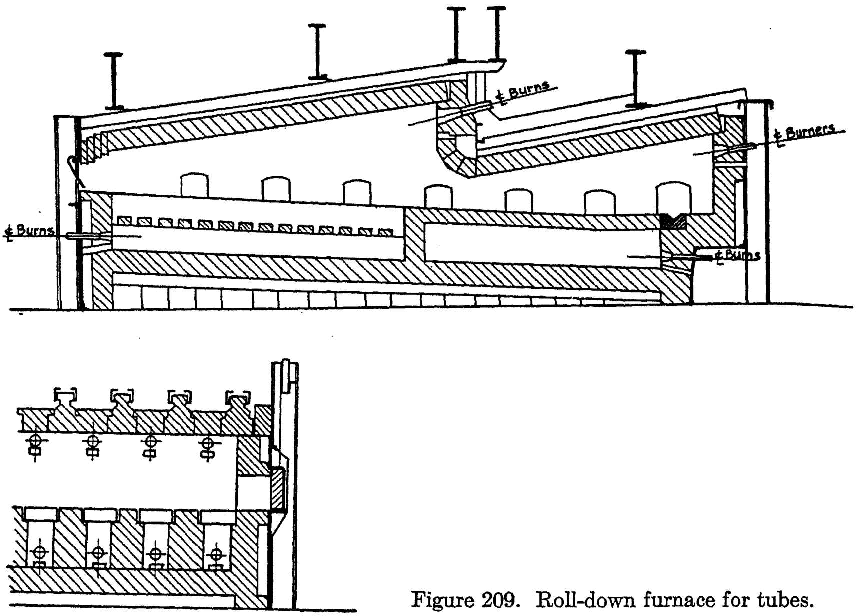



Figure 209. Roll-down furnace for tubes.

Automatic control of air-gas ratio and temperature is applied in order to insure control of scale on the surface of the tube and uniform metallurgical results in the steel structure. The tubes are discharged on a chain cooling bed for cooling at a uniform rate, with space allowed between adjacent tubes.

The only remaining heat application of any importance in tube manufacture is involved in the coating of the finished tube, as in galvanizing. This process has been discussed at some length in the preceding section, and the only difference is in the fact that the kettles for tube galvanizing are deeper than they are for wire products. This increase in depth calls for a difference in the method of firing the galvanizing setting, because most of the heat is transmitted through the sides of the kettle. Impact firing, radiant tubes, and recirculation heating, all as described for wire kettles,

are used for this type of kettle. Because of the depth of the kettle and the weight of the contents, the kettle is usually built on a solid bottom of refractory.

## Furnaces for Sheet and Strip

In this section the subject will be the furnace considerations involved in the making of steel sheets and strip, and the study of these heating problems will follow the outline established in the preceding sections.

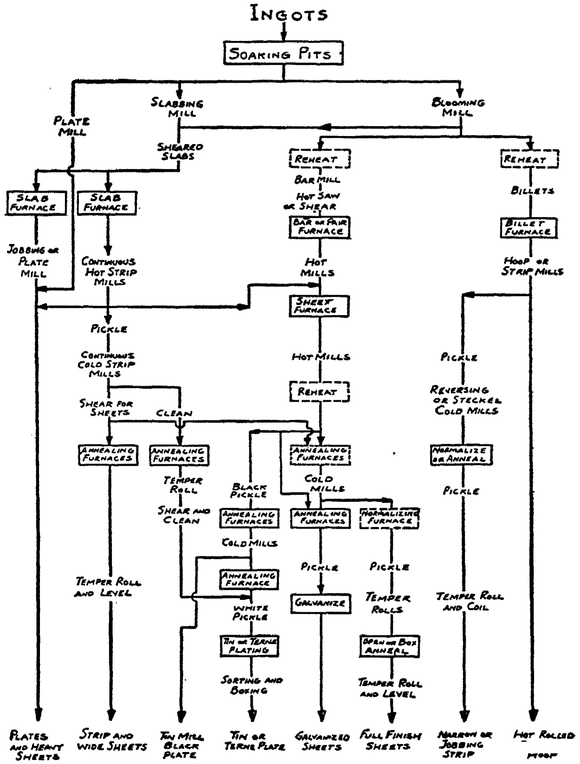



Figure 210. Chart of material flow in the manufacture of sheets and strips.

The graphical chart of Figure 210 shows an outline of the principal processes involved in sheet and strip manufacture. The outline of each process is very general, the principal purpose of the chart being to locate the chief points of heat application, which are emphasized by boxes in the diagram. Where heat is applied only in some cases the box is shown in dotted lines.

As in the case of all preceding sections, the first application of heat is found to be in the soaking pits, which prepare the ingots for rolling on the blooming or slabbing mill.

Referring to Figure 210, it will be seen that plates may be rolled direct from the ingot, or from slabs which require intermediate heating. Plates are either sheared on all sides or edge-rolled in universal mills; but in all cases they require careful and uniform heating for proper rolling. The relatively small number of plate mills and their early date of installation have resulted in furnace equipment which in most instances is not as modern as that required for the newer strip mills requiring slab heating. The slabs for plate mills may be heated in regenerative or recuperative batch furnaces, or in the usual continuous pusher furnaces. In the case of batch furnaces, the older installations are of the regenerative or reversing type with large underground checker chambers, while the newer installations

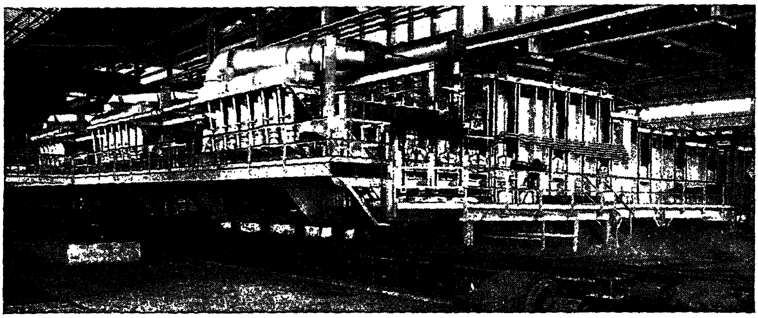


Figure 211. Slab-heating furnaces on a recent continuous strip mill.

are of the recuperative type. In this case, the air for combustion is preheated in metallic recuperators. Material to be heated is usually handled by means of mechanical charging machines through the doors along the front of such furnaces, and the burners are located at the end of the furnace.

Where continuous slab furnaces are used in older installations, they are generally of the Morgan design with longitudinal arches on water-cooled pipes; more modern designs incorporate the suspended-arch type of construction. Figure 211 shows typical slab-heating furnaces on one of the modern strip mills, and illustrates the latest design in this class of furnace. The heating capacity of each furnace is usually 50 net tons per hour on cold steel, and two or three furnaces are installed as required by the mill. For this capacity the furnace size is about 16 to 20 ft wide and about 80 ft long inside, with an average hearth area of 1400 sq ft, which corresponds to a maximum heating rate of 70 lbs per sq ft of hearth area per hour.

The outstanding improvements in these furnaces are the use of suspended flat arches, automatic control, and insulation. The slabs are pushed on water-cooled skids through the first zone of the furnace, where heat is usually applied from above and below the steel. Cheap fuel, such as producer gas, is frequently used in this first zone where uniformity and

surface conditions are not so important. In the second zone of the furnace the steel is pushed over a refractory bottom and is heated from above only by a refined fuel such as natural gas.

Both zones of the furnace are separately and automatically controlled for temperature, and automatic control of air-gas ratio and furnace pressure are also frequently applied. Recuperators reheat the combustion air to about 800 deg F, utilizing heat from the waste gases on their way to the stack; the average economy of these furnaces is about 1.7 million Btu per ton of steel heated. Slabs vary in size up to 6 in thick, 60 in wide, and 16 ft long, and in shorter lengths are sometimes pushed in two rows through the furnace. The temperature of the steel leaving these furnaces is about 2350 deg F. Practically all the usual fuels and mixtures of fuels, including blast-furnace gas, have been used on this type of furnace.

Hoop iron, which is a form of thin and narrow strip, is about the only sheet or strip product rolled from billets, and the standard billet-heating furnaces employed for this purpose do not require any special attention.

Sheet products occupy a classification distinct from plates or strip, and in turn comprise a number of distinct products. The distinction between sheets and plate is in thickness and size, and in the use. There is some overlapping of the classification with regard to thickness, where the terms "light plate" and "jobbing sheets" are confused. Plates are definitely above $\frac{3}{16}$-in thick and sheets under 10 USS gage. From sheet mills the product is usually limited to 54 in wide by 180 in long; larger sheets are generally made on the large strip mills which can roll up to 94 in wide at the present time. Sheets are subject to many severe forming operations and must have surface and physical qualities not required in plates. The classification of sheets includes jobbing sheets (10 to 16 gage), sheets (10 to 30 gage), and tin plate (14 to 38 gage). Some sheet mills start with hot-rolled plates from the strip mill, but most mills use sheet bars; these are the first products to require heating in the making of the sheets.

Sheet bars until recently have been of standard 8-in width (with length about equal to the width of sheet to be rolled) which limit was fixed by the maximum weight for comfortable hand operation. The competition with strip mills has now increased the width to 10 in in many cases and to 16 in in some instances, with mechancial handling to take care of the increased weight. New types of mills have also been developed to produce greater roughed and finished tonnage at lower costs.

Whether the mill is manually operated or mechanized, the procedure is generally to heat the sheet bar for roughing on one or two mills. The roughed sheets are matched in twos, threes, or fours, depending on the gage, and heated in "pack furnaces" for further rolling. For lightest sheets, the packs are also doubled, until finally as many as eight thicknesses are rolled together, with additional heating operations in the process.

The earlier types of pair furnaces for heating sheet bars, and which are still used in most hand mills, are either batch-type furnaces or pusher-type continuous furnaces, while the more recent installations use a chain conveyor for carrying the bars through the furnace.

The batch-type pair furnace is a simple side-fired furnace with rectangular hearth and reverberatory roof (higher on one side than on the other). The fuel is fired behind a bridgewall on one side or through the rear wall, and the waste gases are removed through sidewall flues connected to a stack carried on the structural binding of the furnace, as shown in Figure 212. The bars are handled with tongs through the small front doors. In many

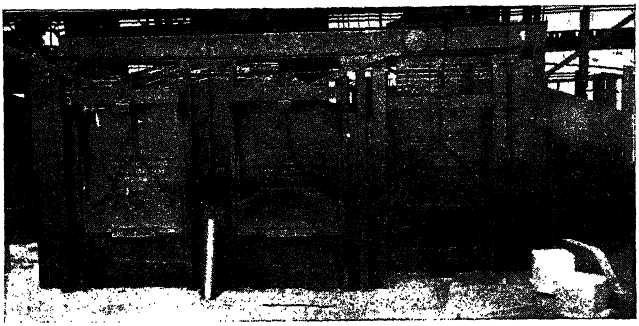


Figure 212. Sheet and pair furnace. Chamber at right is for pairs, while the two chambers at left are for sheet packs.

cases the pair furnace is built in a common binding with a sheet heating furnace of almost identical design for heating the breakdowns from the roughing mill. Such combination furnaces are known as "sheet and pair" furnaces, and the two chambers differ only in the doors, which are larger on the sheet furnace chamber to accommodate the larger dimensions of the breakdowns.

Sheet bars are heated to a maximum temperature of about 1600 deg F in the pair furnace, and great care is necessary to obtain uniform rolling and proper surface conditions on the breakdowns. Such furnaces have been found to be a good application for the luminous type of burner. The developments in burner design and automatic control have been of great assistance in the heating of bars and breakdowns.

The early continuous bar-heating furnaces of the pusher type used rails on which the bars were pushed on edge and at a slight angle to the vertical, as shown in Figure 213. A feature of some of these furnaces is the gravity catch at the charging end, which holds the bars in position after the stroke of the pusher has been completed and the pusher head has returned to pushing position.

A more modern furnace for heating sheet bars is that in which the bars

are carried on fingers attached to malleable iron or steel chains traveling below the level of the hearth refractories. The chain is not only protected from excessive heat, but also does not carry any excessive amount of heat out of the furnace. The carrying fingers are of alloy and travel through slots in the refractory hearth. These fingers support the bars above the hearth to permit circulation of heat below the bars. This type of furnace is usually fired from both sides, either direct-fired for gas or fired behind a bridgewall for fuel oil.

These furnaces are frequently built for heating both pairs and packs, in which case two sets of chains are provided with separate speed control.

Figure 213. Early continuous Costello sheet bar furnace, pusher type.

One set of chains carries the bars while the other set carries the packs for reheating. The chamber in these single or double furnaces varies from 54 to 84 in wide, and from 50 to 90 ft long, and the rate of production is about 50 lbs per sq ft of hearth per hour. In many cases the two sides of a double furnace are separated by a dividing wall through the furnace to create, in effect, two separate furnaces in a common setting.

Figure 214 shows a rotary producer gas-fired furnace for heating stainless steel sheet bars. In this furnace the bars are charged in one door and after being carried through the furnace on the rotary hearth, are discharged through the other door. Tangentially arranged gas burners are used to heat the furnace, and no alloy parts are involved in the continuous operation.

As has already been stated, the development of the sheet and pack heating furnaces has paralleled that of the pair furnace. The batch furnace for smaller mills and the continuous conveyor for mechanized sheet mills are often built in common settings with the pair furnace if indicated by the mill arrangement.

Sheet furnaces are also built with disc roller conveyors and with walking beams for conveying the packs through the furnace. In the latter case,

the walking beams are built of heat-resisting alloy and are arranged to permit firing of the fuel below as well as above the sheets.

After shearing, the finished hot-rolled pack is opened and the sheets are ready for the finishing operations. These operations depend upon the type of finished sheet required. They include pickling in acid; cold-rolling to produce surface conditions and to change the physical properties of the sheet; annealing to offset the effect of grain elongation in rolling and to increase ductility; normalizing to recrystallize and refine the grain of all hot-rolled and some cold-rolled sheets; box annealing for increasing ductility and for relieving rolling strains; and bright annealing in special cases.

Open annealing is accomplished in an open furnace at about 1600 deg F and is sometimes referred to as blue annealing, from the appearance of the

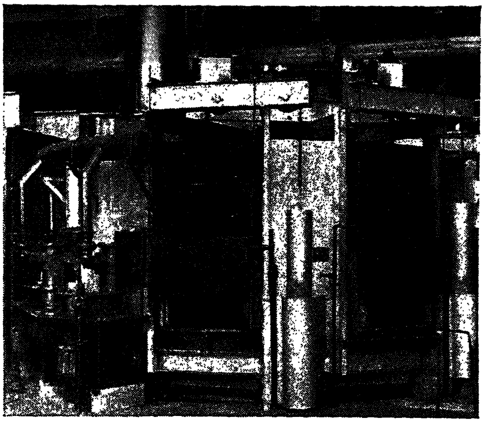


Figure 214. Rotary furnace, gas fired, for heating stainless steel sheet bars.

oxidized surface produced. This process is used only in the older method of sheet making by hot-rolling to size. The modern strip mill with cold mills for finishing has dispensed with this type of annealing.

The majority of the open-annealing furnaces are either the roller-hearth or chain-conveyor type. Figure 215 shows a roller-hearth annealing furnace in which the alloy rollers are driven from the outside of the furnace. The sheets are carried on waster sheets to prevent scratching of the product; they may be charged as separate sheets or in piles of several sheets of light gage. The furnace is generally limited to about 6 ft wide and the production averages about 30 lbs of steel (including the waster sheets) per sq ft of hearth per hour. Burners arranged along both sides of the furnace fire through the sidewalls above the level of the sheets. Rollers are discussed in more detail in connection with discussion of normalizing equipment.

The chain-type furnace is similar in design to the sheet and pack furnaces already described. Open-annealing furnaces of any design are operated with a heavily reducing atmosphere to obtain tight blue scale on the sheets.

Normalizing furnaces are also a standard equipment in hot-rolled sheet mills for refining the grain of the steel, but are only occasionally required in the manufacture of cold-rolled sheets and strip. The development of this furnace has been one of the most interesting and difficult of furnace problems, principally because of the high temperature, the increasing width of furnace required, and the physical nature of the product to be conveyed.

Sheets are heated for only about 4 minutes for normalizing, and weights are very small per square foot of space occupied, so that some form of continuous furnace must be employed for any large production, to avoid excessive handling.

The first of these furnaces were of the roller-hearth type, with water-cooled rollers, and were built with an inside width not exceeding about 6 ft

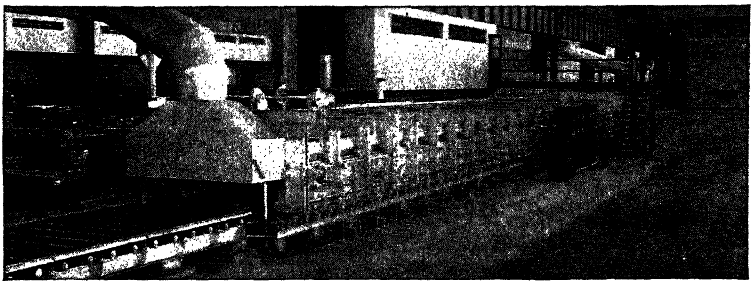


Figure 215. Roller-hearth furnace for open annealing of sheets.

to accommodate the narrow sheets made in the hand mills of that time. The next important development was that of heat-resisting alloys, and one of the first extensive applications of these new materials in steel mills was in so-called dry rollers (without water-cooling) for sheet normalizing furnaces. Various designs, including shafts with renewable discs, were developed rapidly (see Chapter 6) and successful installations were made. The temperature in these furnaces is about 2000 deg F for a sheet temperature of about 1700 deg F, which is close to the limit for these alloys even today. However, the rotating feature of these rollers is of great assistance in this respect, because the allowable stress is twice as great for rotating parts as it is for stationary applications.

The next problem to arise came from the rapid increase in width of sheets to be normalized, so that the inside furnace width increased to 9 ft in a short time. Since in a beam of the kind represented by these roller shafts the stress increases as the square of the span, the problem of alloy design becomes exceedingly difficult. Several new designs were developed as the result of this increase in width. In one case, double bearings were used outside the furnace to permit a cantilever stub shaft to extend to the inside

of the furnace for supporting the roller at each end. By this device the effective span of the roller was decreased from the overall outside width of the furnace to the inside width of the chamber. Another arrangement consisted of alloy rollers mounted on the bottom of the furnace for supporting the shafts at intermediate points (Figure 160). Still another design abandoned the roller hearth for wide furnaces, and used an alloy walking beam for carrying the sheets through the furnace.

These furnaces are divided into zones for heating, soaking, and variable cooling, according to the metallurgical requirements of the product. Water pipes and water jackets are used for quick cooling where required, while the heating sections are fired by side burners at frequent intervals, with good temperature and combustion control. The temperature-control equipment is particularly important because of the damage to alloy parts resulting from temperatures even slightly in excess of those required. The maximum rate of heating in these furnaces is 30 lbs of steel per sq ft of hearth area per hour, which includes the weight of waster sheets. A high temperature differential is economical in furnace size and is permissible in this case because there is no danger of uneven heating through the thickness of a thin sheet of metal. The length of these furnaces varies between about 70 and 130 ft, of which about 50 per cent is cooling zone.

The atmosphere in normalizing furnaces is very reducing to produce a light thickness of tight scale on the heated sheets.

Both hot mills and cold mills for almost all forms of sheet and strip use some form of box annealing furnace for heating the product at temperatures below 1400 deg F, and the development of these furnaces has also been an interesting story in furnace design. Until about 1930, all sheet products were annealed in cast steel boxes with sealed covers, which were usually charged into a large batch-type furnace on iron balls. During the many years preceding that time gradual improvements were made in the methods of firing and controlling these furnaces, but little change was made in the fuel economy or labor-saving features of the process. Natural gas or prepared gas was introduced into the box for protecting the surface of the deoxidized sheet, and steam was sometimes introduced for blueing the finished product. A few installations were made of large tunnel kilns for continuously heating the boxes, but these were applicable only where a large tonnage of similar product was involved. In the case of coiled strip of high quality and in relatively narrow width, the material was sealed in heavy cast containers, in some cases with iron borings to reduce decarburization, and heated in car type or other batch furnaces.

About 1930, the hood-type furnace was developed for this work and has been almost universally adopted since that time, although many box furnaces are still in use in improved form. In principle the hood furnace is a refractory-lined and heated cover which can be lifted over a light alloy

sheet container in which the product is sealed and in which it can be cooled without moving after the heated cover has been removed. Several bases and retorts are provided with each cover to allow for heating, cooling, and preparing the charge.

Figure 216. Rectangular annealing cover for sheets, showing additional bases.

For the annealing of sheets and large coils the furnace cover is in rectangular form, as shown in Figure 216, which also shows the various bases in conjunction with the cover. The retort over the piles of sheets or stacks of coils is of sheet metal, either alloy or firebox steel, and is sealed at the bottom by either sand or an external oil seal. The heating of the cover may be by electric elements, radiant tubes, or by direct-fired burners.

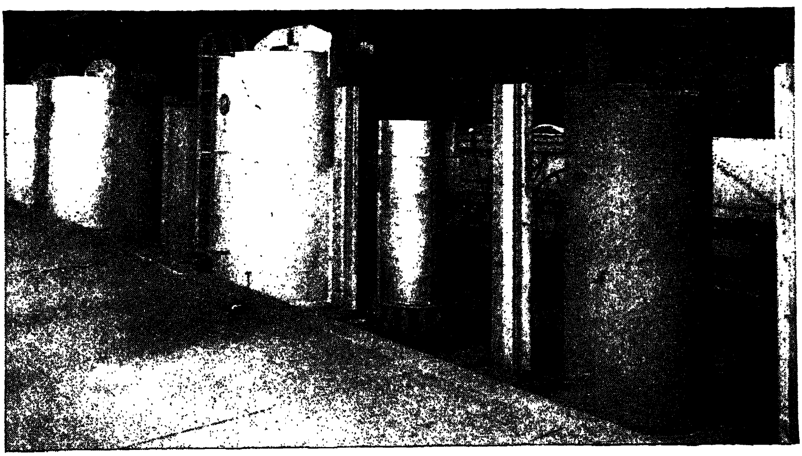


Figure 217. Battery of cylindrical bell type, electrically heated, furnaces for coiled strip.

For coiled strip in smaller quantities the round hood cover has been developed to cover one stack of coils, as in the electrically heated hood furnace of Figure 217. The radiant tubes used for firing these covers are sometimes arranged vertically, horizontally, or in a diagonal arrangement.

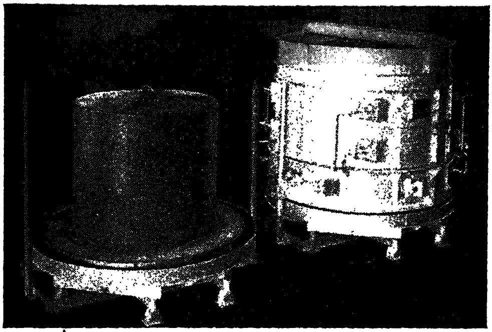


Figure 218. Direct-fired circular hood furnace.

Figure 218 shows a direct-fired hood furnace with small gas burners for heating in a simple but very uniform manner.

Circulation fans are frequently provided in the permanent retort bases (Figure 219). Suitable protective gas from combustion generators is provided in the retort for scale-free or bright annealing as required. In the case of certain steels which require a very slow cooling, an insulated cooling cover is provided to place over the charge after the heating furnace is removed. This arrangement provides a slower cooling rate than is ob-

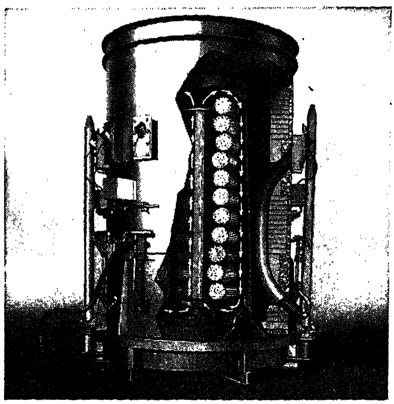


Figure 219. Cutaway section of Wilson hood furnace showing circulating fan.

tained with the uncovered retort, and increases the production by eliminating the necessity for slowly cooling the heating furnace.

The rectangular hood furnaces are made to cover corrugated sheet retorts up to 20 ft long by 10 ft wide by 7 ft high, with a loading capacity up to 100 net tons of sheets or coils. An average retort size used in the sheet mills is about 16 ft long by 7 ft wide by 5 ft high, with a loading capacity

of 75 to 80 net tons. The heating portion of the annealing cycle is in the neighborhood of 60 hours, and the production per hour varies from 2500 to 3000 lbs. The average overall economy of these furnaces is about 1.5 million per net ton annealed. The cooling time is about twice the heating time in most cases.

The diameter of coils annealed in circular retorts is usually about 42 in, and the retort is 54 in in diameter. The loading height varies in most cases from 60 to 80 in, although these retorts have been made up to 130 in high with good results. The charging capacity of an average retort of 54 in diameter by 60 in effective height is about 15,000 lbs of coils, and the

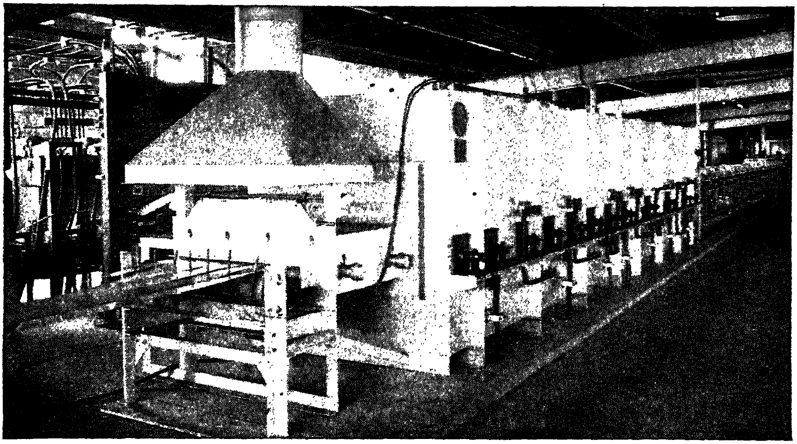


Figure 220. Bright annealing furnace for cold-rolled strip.

heating cycle varies from 12 hours for low-carbon steel to 30 hours for high-carbon and alloy steels. The corresponding production is from 500 to 1500 lbs per hour.

The control of temperature in these furnaces is important for uniform and satisfactory results. Electric and direct-fired furnaces of the circular type should have two zones of automatic control, on account of the difference in heat requirements at the top and bottom of the furnace. Furnaces of the tube-fired type are usually provided with a dual control. At the beginning of each cycle the control is actuated from tube element temperature to prevent the overheating of these tubes. When the outside of the steel charge has reached the desired temperature the control automatically shifts to the steel temperature for the remainder of the soaking period.

The continuous bright annealing of cold-rolled strip is being applied in an increasing number of processes where maximum softness is not required, because savings can be realized by the rapid annealing of the product, as compared with the days required in the box or cover furnaces. Figure 220 shows an electrically heated furnace of this type. The containing shells

of both heating and water-cooled cooling sections are gas-tight to contain the prepared bright-annealing atmosphere, and the strip is supported on rollers in its travel through the furnace. Such furnaces are also fired by gas-fired radiant tubes.

Bright-annealing atmospheres used in either the retort or continuous type of annealing furnaces are usually made from cracked hydrocarbon gases such as natural gas, but dissociated ammonia is also used in some applications, particularly for the annealing of stainless grades and for silicon sheets and strip.

Metal coating furnaces in the sheet industry include principally those for galvanizing, tinning, and terne coating (lead and tin mixture).

Galvanizing is carried on in a manner similar to that for products already discussed, except that sheets are handled in the galvanizing kettle by means of a special machine mounted in the spelter bath. This machine takes care of handling the clean sheets through the flux and zinc baths and wipes off excess zinc before discharging them on the conveyor which takes them to the leveller. The galvanizing pot is of low-carbon steel and is fired by burners arranged as described for the manufacture of rods and wire in the preceding discussion.

The principles involved in the hot-dip process of tinning are the same as for galvanizing and the heated kettle containing the molten tin is so similar to those already described that little comment is necessary. The weight of tin coat varies from 0.5 to 7.0 pounds of tin per base box, which varies from 95 to 128 lbs of finished tin plate. The cast-iron pot is in two compartments, and as in the case of sheet galvanizing, the tinning machine for handling the sheets is located in the pot. In operation the clean sheet is fluxed, dipped in tin, drawn through palm oil, and delivered to the conveyor which takes it to the cleaning machine for polishing and removing the palm oil by absorbent bran or other material. Electrolytic tinning of strip is an interesting development for the close control of tin coat, but requires no unusual furnace equipment.

Terne plate is made by a method identical with tin plating as far as furnaces are concerned, except that a different plating mixture is used in the kettle. Terne plates were originally made for roofing purposes, but are also used now for deep drawing and for some types of containers.

The annealing of stainless sheets is a current problem in the steel mills. Stainless strip is annealed in strands in an open furnace, and sheets have been annealed continuously in roller-hearth furnaces. However, the high temperatures involved cause high alloy replacement cost and open firing is not very satisfactory for final annealing of stainless sheets which are to be polished. For these reasons, the batch-type muffle furnace with speed fork handling remains the usual furnace choice, but there is a great deal of interest in obtaining a good continuous furnace for this purpose.